PB84-175959

Pilot-Scale Parametric Testing of Spray Dryer SO2 Scrubber for Low-to-Moderate Sulfur Coal Utility Applications

Cottrell Environmental Sciences, Somerville, NJ

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Mar 84

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-84-045	2.	3. RECIPIENT'S ACCESSION NO. PB84 175959
4. TITLE AND SUBTITLE Pilot-scale Parametric Testing of Spray Dryer SO2 Scrubber for Low-to-moderate Sulfur Coal Utility Applications		5. REPORT DATE March 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) N. J. Stevens, G. B. Manavizadeh, G. W. Taylor, and M. J. Widico		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Cottrell Environmental Sciences, Inc. P.O. Box 1500 Somerville, New Jersey 08876		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-3190
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 2/80 - 3/81
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Theodore G. Brna, Mail Drop 61, 919/541-2683.

16. ABSTRACT The report gives results of a comprehensive, pilot, dry, SO2 scrubbing test program to determine the effects of process variables on SO2 removal. The ranges of process variables were: inlet flue gas SO2 concentration, 185-2150 ppm; stoichiometric ratio, 0.5-6.4 moles lime/mole SO2; recycle ratio, 0-4.3 lb recycle solids/lb fresh lime; inlet flue gas temperature, 226-340 F; spray dryer flue gas outlet temperature, 128-210 F; and fabric filter temperature, 117-200 F. In the spray dryer, stoichiometric ratio, flue gas temperature approach to adiabatic saturation, and temperature drop across the spray dryer significantly affected SO2 removal. In the fabric filter, stoichiometric ratio and temperature approach to adiabatic saturation controlled SO2 removal. Recycling FGD/fly ash product solids enhanced SO2 removal over that of lime-only once-through operation. Without fresh lime, recycle solids and fly ash solids in separate tests each produced about 20% SO2 removal at a stoichiometry of 1 mole alkali/mole SO2. Over the range investigated (30-90+ %), SO2 removal correlated well with the key spray dryer and fabric filter process parameters. The technoeconomic evaluation, based on test results, showed that a dry SO2 scrubbing system is economical compared to limestone wet FGD/particulate control systems for coal levels up to about 1.5-1.8 wt %.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Sulfur Oxides	Pollution Control	13B	07B
Coal	Calcium Oxides	Stationary Sources	21D	
Flue Gases	Stoichiometry	Fabric Filters	21B	07D
Desulfurization	Fabrics	Technoeconomics	07A, 07D	11E
Scrubbers	Filters	Particulate	13I	14G
Spray Drying	Economics		13H	05C

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 267
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

PB84-175959

EPA-600/7-84-045
March 1984

PILOT-SCALE PARAMETRIC TESTING OF SPRAY DRYER SO_2 SCRUBBER FOR LOW-TO-MODERATE SULFUR COAL UTILITY APPLICATIONS

by

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Contract No. 68-02-3190

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Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Office of Environmental Engineering and Technology
Washington, DC 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

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ABSTRACT

A comprehensive dry SO_2 scrubbing test program was conducted which involved an in-depth field pilot study at the Comanche Station of Public Service Company of Colorado. The test program investigated the effects of a number of process variables on SO_2 removal. The ranges of process variables tested during the pilot program were: inlet flue gas SO_2 concentration from 185 to 2150 ppm, stoichiometric ratio from 0.5 to 6.4 moles lime/mole SO_2, recycle ratio from 0 to 4.3 lb recycle solids/lb fresh lime, inlet flue gas temperature from 226 to 340°F, spray dryer flue gas outlet temperature from 128 to 210°F, and fabric filter temperature from 117 to 200°F.

In the spray dryer, stoichiometric ratio, flue gas temperature approach to adiabatic saturation, and temperature drop across the spray dryer significantly influenced SO_2 removal. In the fabric filter, stoichiometric ratio and temperature approach to adiabatic saturation controlled SO_2 removal. Recycling of FGD/flyash product solids was found to enhance SO_2 removal over that of lime-only, once-through operation. In the absence of fresh lime, recycle solids and flyash solids in separate tests each produced about 20 percent SO_2 removal at a stoichiometry of 1 mole alkali/mole SO_2. Over the range investigated from 30 to 90+ percent, SO_2 removal correlated well with the key spray dryer and fabric filter process parameters.

The final phase of the field test program consisted of a continuous demonstration of dry SO_2 scrubbing technology. The 5-day continuous run demonstrated that the spray dryer/fabric filter system is able to consistently achieve the 70 percent SO_2 removal level required to meet the New Source Performance Standards for low sulfur coal.

Pilot test results related to stoichiometry, recycle ratio, and unit operating temperatures provided the basis for a technoeconomic evaluation. The technoeconomic study showed that a dry SO_2 scrubbing system is economic compared to limestone wet FGD/particulate control systems (fabric filter/limestone scrubber, ESP/limestone scrubber) for coal sulfur levels up to about 1.6 to 1.9 wt. percent.

Dry SO_2 scrubbing solid waste characteristics also were evaluated. Spray dryer product solids are coarser than fabric filter solids (30 to 35 µm versus ~ 10 µm mean diameter). Product solids chemical compositions from the two sources are similar, but spray dryer solids contain higher concentrations of unused reagent and fabric filter solids contain increased percentages of FGD products. Curing for one month at 72°F and ~ 100 percent relative humidity increased the cohesive strength of the waste solids by a factor of 3 to 6. Product solids leachate heavy metal contents are significantly less than hazardous waste maximum allowable levels.

CONTENTS

Abstract iii
Figures v
Tables xi
Abbreviations and Symbols xiv
Acknowledgement xvi
1. Introduction 1
2. Conclusions 3
3. Dry SO_2 Scrubbing Pilot System 8
4. Pilot Test Program 17
5. Major Process Variable Studies 19
6. Spray Dryer Atomizer Variables 81
7. Lime Slaking 93
8. Process Demonstration 107
9. Product Solids 117
10. Waste Characterization Studies 137
11. Technoeconomic Study 148
References 168

Appendices

A. Spray Dryer/Fabric Filter Pilot Test Results 170
B. Chemical and Physical Analyses 226
C. Analytical Methods 241
D. Glossary 248
E. Conversion Factors 250

FIGURES

Number		Page
3-1	Dry SO_2 Scrubbing Pilot Plant	9
3-2	Dry SO_2 Scrubbing Pilot Flow Schematic	10
3-3	Spray Dryer/Fabric Filter Process Flow Diagram	14
5-1	Effect of Stoichiometry on Spray Dryer SO_2 Removal -- Lime-Only Operation	23
5-2	Effect of Stoichiometry on Spray Dryer SO_2 Removal at Moderate Spray Dryer Temperature Drop	24
5-3	Effect of Stoichiometry on Spray Dryer SO_2 Removal at Low Spray Dryer Temperature Drop	25
5-4	Effect of Stoichiometry on Spray Dryer SO_2 Removal at High Spray Dryer Temperature Drop and High Approach to Adiabatic Saturation Temperature	26
5-5	Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal -- Lime-Only Operation	28
5-6	Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal -- Recycle Operation	30
5-7	Effect of Temperature on Spray Dryer SO_2 Removal	31
5-8	Effect of Adiabatic Saturation Temperature on Spray Dryer Solids Moisture Content	32
5-9	Effect of Spray Dryer Temperature Drop on Spray Dryer SO_2 Removal -- Lime-Only Operation	34
5-10	Effect of Spray Dryer Temperature Drop on Spray Dryer SO_2 Removal - Recycle Operation	36
5-11	Comparison of Two Levels of Spray Dryer Temperature Drop for Spray Dryer SO_2 Removal	37
5-12	Effect of Spray Dryer Temperature Drop on Spray Dryer SO_2 Removal at Three Levels of Temperature Conditions	38

FIGURES (CONTINUED)

Number — Page

5-13 Effect of Recycle Ratio on Spray Dryer SO_2 Removal................. 39

5-14 Effect of Residence Time on Spray Dryer SO_2 Removal -- Lime-Only Operation.. 41

5-15 Effect of Residence Time on Spray Dryer SO_2 Removal -- Recycle Operation.. 43

5-16 Effect of Inlet SO_2 Concentration on Spray Dryer SO_2 Removal -- Lime-Only Operation... 45

5-17 Effect of Inlet SO_2 Concentration on Spray Dryer SO_2 Removal -- Recycle Operation... 46

5-18 Parity Plot of Observed and Predicted Spray Dryer SO_2 Removal -- Lime-Only Operation... 49

5-19 Comparison of Observed and Predicted Spray Dryer SO_2 Removal at High Spray Dryer Temperature Drop.............................. 50

5-20 Comparison of Observed and Predicted Spray Dryer SO_2 Removal at Moderate Spray Dryer Temperature Drop.......................... 51

5-21 Parity Plot of Observed and Predicted Spray Dryer SO_2 Removal -- Recycle Operation... 52

5-22 Effect of Stoichiometry on Fabric Filter SO_2 Removal -- Lime-Only Operation... 55

5-23 Effect of Stoichiometry on Fabric Filter SO_2 Removal -- Recycle Operation... 56

5-24 Effect of Pressure Drop on Fabric Filter SO_2 Removal............... 57

5-25 Effect of Adiabatic Saturation Temperature on Fabric Filter SO_2 Removal.. 59

5-26 Effect of Adiabatic Saturation Temperature and Stoichiometry on Fabric Filter SO_2 Removal..................................... 60

5-27 Effect of Recycle Ratio on Fabric Filter SO_2 Removal............... 62

FIGURES (CONTINUED)

Number Page

5-28 Effect of Air-to-Cloth Ratio on Fabric Filter SO_2 Removal -- Lime-Only Operation.......... 63

5-29 Effect of Air-to-Cloth Ratio on Fabric Filter SO_2 Removal -- Recycle Operation.......... 64

5-30 Effect of Inlet SO_2 Concentration on Fabric Filter SO_2 Removal -- Lime-Only Operation.......... 66

5-31 Effect of Inlet SO_2 Concentration on Fabric Filter SO_2 Removal -- Recycle Operation.......... 67

5-32 Parity Plot of Observed and Predicted Fabric Filter SO_2 Removal -- Lime-Only Operation.......... 70

5-33 Parity Plot of Observed and Predicted Fabric Filter SO_2 Removal -- Recycle Operation.......... 72

5-34 SO_2 Removal in Spray Dryer Relative to Total SO_2 Removal.......... 73

5-35 Parity Plot of Observed and Predicted Overall SO_2 Removal -- Lime-Only Operation.......... 75

5-36 Comparison of Observed vs. Predicted Overall SO_2 Removal -- Lime-Only Operation.......... 76

5-37 Overall SO_2 Removal -- Recycle Operation.......... 77

6-1 Effect of Atomizer Speed on Spray Dryer SO_2 Removal.......... 82

6-2 Effect of Flue Gas Flow Rate and Atomizer Speed on Spray Dryer Solids Moisture Content.......... 83

6-3 Effect of Atomizer Speed on Spray Dryer SO_2 Removal.......... 85

6-4 Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal.......... 87

6-5 Solids Collection in Spray Dryer Relative to Total Solids Collection.......... 88

6-6 Effect of Residence Time on Spray Dryer Solids Moisture Content.... 89

FIGURES (CONTINUED)

Number		Page
6-7	Effect of Wheel Type on Spray Dryer SO_2 Removal	91
6-8	Effect of Gas Vane Type on Spray Dryer SO_2 Removal	92
7-1	Effect of Lime Slaking Temperature on Spray Dryer SO_2 Removal	94
7-2	Effect of Lime Slaking Temperature on Particle Size Distribution	95
7-3	Effect of Lime Slaking Water Quality on Spray Dryer SO_2 Removal	97
7-4	Effect of Slaking Water Quality on Lime Particle Size Distribution	98
7-5	Effect of Lime Source on Spray Dryer SO_2 Removal	100
7-6	Effect of Lime Source on Particle Size Distribution	101
7-7	Effect of Lime Slaker Paddle Speed on Spray Dryer SO_2 Removal	102
7-8	Effect of Slaker Paddle Speed on Lime Particle Size Distribution	103
7-9	Slaked Lime Scanning Electron Micrographs	105
8-1	Process Demonstration Test Results -- Overall SO_2 Removal and Overall Stoichiometric Ratio	109
8-2	Process Demonstration Test Results -- Spray Dryer SO_2 Removal and Spray Dryer Stoichiometric Ratio	110
8-3	Process Demonstration Test Results -- Spray Dryer Outlet Temperature and Spray Dryer Solids Moisture Content	111
8-4	Process Demonstration Test Results -- Spray Dryer Solids Moisture Content and Spray Dryer Solids as Percent of Total Solids Collected	112
8-5	Process Demonstration Test Results -- Fabric Filter Inlet and Midpoint Temperatures, Fabric Filter Solids Moisture Content	113
8-6	Process Demonstration Test Results -- Spray Dryer and Fabric Filter Inlet Temperatures, Spray Dryer Exit Temperature	114
9-1	Product Solids and Comanche Fly Ash Scanning Electron Micrographs	118

FIGURES (CONTINUED)

Number — Page

9-2 Effect of Recycle Solids Source on Spray Dryer SO_2 Removal........ 124

9-3 Effect of Ball Milling Recycle Solids Blend on Spray Dryer SO_2 Removal.. 126

9-4 Effect of Ball Milling Recycle Spray Dryer and Fabric Filter Solids on Spray Dryer SO_2 Removal.................................. 127

9-5 Effect of Ball Milling on Spray Dryer Particle Size Distribution... 128

9-6 Effect of Ball Milling on Fabric Filter Particle Size Distribution. 129

9-7 Effect of Ball Milling on Fly Ash Particle Size Distribution....... 130

9-8 Fly Ash Reactivity for Spray Dryer SO_2 Removal.................... 132

9-9 Fly Ash Reactivity for Overall SO_2 Removal........................ 133

9-10 Recycle Solids Reactivity for Spray Dryer SO_2 Removal............. 134

9-11 Effect of Available Alkalinity on Spray Dryer SO_2 Removal.......... 135

11-1 Spray Dryer/Fabric Filter Process Flow Diagram...................... 150

11-2 Wet FGD Scrubber/Particulate Control Process Flow Diagram.......... 153

11-3 Capital Investment Comparison at 0.6 Wt.% Sulfur Coal............. 161

11-4 Capital Investment Comparison at 1.0 Wt.% Sulfur Coal............. 162

11-5 Capital Investment Comparison at 1.5 Wt.% Sulfur Coal............. 163

11-6 Unit Capital Investment Cost Sensitivity........................... 164

11-7 Spray Dryer/Fabric Filter Operating Cost Sensitivity.............. 165

11-8 ESP/Wet FGD Scrubber Operating Cost Sensitivity................... 165

11-9 Fabric Filter/Wet FGD Scrubber Operating Cost Sensitivity.......... 165

11-10 Lime Reagent Cost Sensitivity..................................... 166

FIGURES (CONTINUED)

Number Page

11-11 Unit Operating Cost Sensitivity.................................... 167

B-1 Comanche Fly Ash Particle Size Distribution.................... 228

B-2 Ash Grove Slaked Lime Particle Size Distribution.................. 231

B-3 Ash Grove Lime Slurry Specific Gravity Dependence on $Ca(OH)_2$ Content.. 232

B-4 Recycle Solids Slurry Specific Gravity Dependence on Solids Content 233

B-5 Comparison of Spray Dryer and Fabric Filter Particle Size Distributions -- Run 105.. 235

B-6 Comparison of Spray Dryer and Fabric Filter Particle Size Distributions -- Run 106.. 236

B-7 Comparison of Spray Dryer and Fabric Filter Particle Size Distributions -- Run 115.. 237

B-8 Comparison of Spray Dryer and Fabric Filter Particle Size Distributions -- Run 130.. 238

B-9 Comparison of Spray Dryer and Fabric Filter Particle Size Distributions -- Run 603.. 239

B-10 Comparison of Spray Dryer and Fabric Filter Particle Size Distributions -- Run 928.. 240

TABLES

Number | Page
3.1 Dilution Water Composition.......... 12
3.2 Instrument Description and Precision.......... 15
4.1 Variables Investigated.......... 18
4.2 Range of Pilot Test Variables.......... 18
5.1 Range of Spray Dryer Variables Investigated, Lime-Only Operation... 21
5.2 Range of Spray Dryer Variables Investigated, Recycle Operation..... 21
5.3 Effect of Stoichiometric Ratio on Spray Dryer SO_2 Removal......... 22
5.4 Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal.......... 29
5.5 Effect of Temperature Drop Across the Spray Dryer on Spray Dryer SO_2 Removal.......... 33
5.6 Effect of Spray Dryer Residence Time on Spray Dryer SO_2 Removal.... 42
5.7 Effect of Spray Dryer Inlet SO_2 Concentration on Spray Dryer SO_2 Removal.......... 44
5.8 Range of Fabric Filter Variables Investigated, Lime-Only Operation. 53
5.9 Range of Fabric Filter Variables Investigated, Recycle Operation... 54
5.10 Effect of Air-to-Cloth Ratio on Fabric Filter SO_2 Removal.......... 61
5.11 Pilot Plant System Reproducibility, Case I.......... 79
5.12 Pilot Plant System Reproducibility, Case II.......... 80
6.1 Effect of Atomizer Speed on Spray Dryer SO_2 Removal.......... 84
7.1 Slaking Water Chemical Compositions.......... 96
7.2 Comparative Lime Analyses.......... 99
7.3 Comparison of Slaked Lime Particle Sizes.......... 104

TABLES (CONTINUED)

Number Page

8.1 Actual vs. Target Demonstration Run Conditions.................... 107

9.1 Product Solids Particle Size Distributions.................... 117

9.2 Product Solids Chemical Composition.................... 119

9.3 Spray Dryer Solids Mineral Analysis.................... 122

9.4 Fabric Filter Solids Mineral Analysis.................... 123

9.5 Effect of Milling on Recycle Solids.................... 125

10.1 Operating Conditions for Pilot Plant Runs Chosen for Waste Characterization Sampling.................... 138

10.2 Product Solids Compacted Densities.................... 139

10.3 Product Solids Triaxial Compression Test Results.................... 141

10.4 Product Solids Permeabilities.................... 142

10.5 Product Solids Leachate Compositions.................... 144

10.6 Product Solids Heavy Metals Analysis.................... 145

10.7 Product Solids Leachate Heavy Metals Content.................... 146

10.8 Product Solids and Flyash Leachate Heavy Metals.................... 147

11.1 Study Design Basis.................... 149

11.2 Criteria/Assumptions for Spray Dryer/Fabric Filter System Design... 151

11.3 Major Equipment List for Spray Dryer/Fabric Filter.................... 151

11.4 Criteria/Assumptions for Electrostatic Precipitator/Limestone Scrubber System Design.................... 152

11.5 Criteria/Assumptions for Fabric Filter/Limestone Scrubber Design... 154

11.6 Major Equipment List for Wet FGD Limestone Scrubber.................... 154

TABLES (CONTINUED)

Number | | Page
11.7 Comparison of System Total Capital Investments.................... 156
11.8 Comparison of System Annual Operating Costs........................ 157
11.9 Annual Operating Costs for Lime Spray Dryer/Fabric Filter.......... 158
11.10 Annual Operating Costs for Fabric Filter/Limestone Scrubber........ 159
11.11 Annual Operating Costs for Electrostatic Precipitator/ Limestone Scrubber.. 159
A.1 Spray Dryer/Fabric Filter Pilot Test Results: Runs 101 - 126....... 170
A.2 Spray Dryer/Fabric Filter Pilot Test Results: Runs 129 - 222....... 174
A.3 Spray Dryer/Fabric Filter Pilot Test Results: Runs 223 - 403....... 178
A.4 Spray Dryer/Fabric Filter Pilot Test Results: Runs 404 - 422....... 182
A.5 Spray Dryer/Fabric Filter Pilot Test Results: Runs 423 - 506....... 186
A.6 Spray Dryer/Fabric Filter Pilot Test Results: Runs 507 - 526R...... 190
A.7 Spray Dryer/Fabric Filter Pilot Test Results: Runs 529 - 610....... 194
A.8 Spray Dryer/Fabric Filter Pilot Test Results: Runs 611 - 811....... 198
A.9 Spray Dryer/Fabric Filter Pilot Test Results: Runs 812 - 836....... 202
A.10 Spray Dryer/Fabric Filter Pilot Test Results: Runs 837 - 920....... 206
A.11 Spray Dryer/Fabric Filter Pilot Test Results: Runs 921 - 953A...... 210
A.12 Spray Dryer/Fabric Filter Pilot Test Results: Runs 954 - 972....... 214
A.13 Spray Dryer/Fabric Filter Pilot Test Results: Runs 701 - 711....... 218
A.14 Spray Dryer/Fabric Filter Pilot Test Results: Runs 901 - 905R...... 222
B.1 Comanche Coal Proximate Analysis (Unit No. 2)...................... 226
B.2 Comanche Coal Ultimate Analysis (Unit No. 2)....................... 226
B.3 Comanche Flyash Mineral Analysis................................... 227
B.4 Comanche Flyash Particle Size Distribution......................... 229
B.5 Ash Grove Quicklime Typical Analysis............................... 229
B.6 Doped Dilution Water Composition................................... 230

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

A --area
AA --available alkalinity
A/C --air-to-cloth ratio
acfm --actual cubic feet per minute
ASTM --American Society for Testing and Materials
AWWA --American Water Works Association
Btu --British thermal unit
C --cohesive strength
CES --Cottrell Environmental Sciences, Inc.
cm --centimeters
dscf --dry standard cubic feet
e.g. --for example (Latin)
EPA --Environmental Protection Agency
ESP --electrostatic precipitator
^oF --degrees fahrenheit
F.D. --forced draft
FF --fabric filter
FGD --flue gas desulfurization
ft --feet
ft^2 --square feet
ft^3 --cubic feet
gal. --gallon
g --gram
gpm --gallons per minute
gr --grain
hr --hour
i --flow gradient
I.D. --induced draft
i.e. --that is (Latin)
in. --inch
IR --infrared
K --coefficient of permeability
K_1 --SO_2 reaction rate parameter
K_2 --SO_2 reaction rate parameter
kW --kilowatt
kWh --kilowatt-hour
lb --pound
L/G --liquid-to-gas ratio
LOI --loss on ignition
LS --limestone scrubber
M --thousand
min --minute
mg --milligram
ml --milliliters
MW --megawatts
N --normality
N/A --not available
ND --none detected
NSPS --New Source Performance Standards
ΔP --pressure drop
ΔP_{FF} --pressure drop across fabric filter
ppm --parts per million
ppmv --parts per million by volume
ppmw --parts per million by weight
psi --pounds per square inch
psia --pounds per square inch absolute
q --rate of flow
r --multiple correlation coefficient
RR --recycle ratio
rpm --revolutions per minute
S --normal stress on shear plane
SCA --specific collection area
SD --spray dryer
se --standard error of estimate
sec --second
SEM --scanning electron micrograph
SR --stoichiometric ratio
T --temperature

$T_{IN/SD}$	--flue gas spray dryer inlet temperature
$T_{IN/FF}$	--flue gas fabric filter inlet temperature
$T_{OUT/SD}$	--flue gas spray dryer outlet temperature
$T_{OUT/FF}$	--flue gas fabric filter outlet temperature
$T_{AS/SD}$	--flue gas spray dryer adiabatic saturation temperature
$T_{AS/FF}$	--flue gas fabric filter adiabatic saturation temperature
$\Delta T_{AS/SD}$	--flue gas approach to adiabatic saturation temperature at spray dryer outlet
$\Delta T_{AS/FF}$	--flue gas approach to adiabatic saturation temperature at fabric filter outlet
ΔT_{SD}	--flue gas temperature drop across spray dryer
ΔT_{FF}	--flue gas temperature drop across fabric filter
T_f	--shearing strength
tan	--tangent
TDS	--total dissolved solids
TGA	--thermogravimetric analysis
TSS	--total suspended solids
TVA	--Tennessee Valley Authority
UV	--ultraviolet
wt.	--weight
yr.	--year

SYMBOLS

Al_2O_3	--aluminum oxide
CO_2	--carbon dioxide
$CO_3^=$	--carbonate ion
Ca^{++}	--calcium ion
$CaCO_3$	--calcium carbonate
CaO	--calcium oxide
$Ca(OH)_2$	--calcium hydroxide
$CaSO_x$	--calcium-sulfur compounds (FGD products)
$CaSO_3 \cdot \frac{1}{2}H_2O$	--calcium sulfite hemihydrate
$CaSO_4$	--calcium sulfate (anhydrous)
Cl^-	--chloride ion
Fe_2O_3	--iron oxide
HCl	--hydrochloric acid
Hg	--mercury
H_2O	--water
K^+	--potassium ion
K_2O	--potassium oxide
Mg^{++}	--magnesium ion
MgO	--magnesium oxide
N_2	--nitrogen
Na^+	--sodium ion
Na_2O	--sodium oxide
O_2	--oxygen
$P_2O_5^=$	--phosphorus pentoxide radical
S	--sulfur
SO_2	--sulfur dioxide
SO_3	--sulfate as SO_3
$SO_3^=$	--sulfite ion
$SO_4^=$	--sulfate ion
SiO_2	--silicon dioxide
TiO_2	--titanium dioxide
Θ	--flue gas spray dryer residence time
ϕ	--angle of internal friction
µg	--microgram
µm	--micrometer
$\sim$	--approximately
ϵ	--SO_2 removal efficiency

ACKNOWLEDGEMENT

We thank the host utility, Public Service of Colorado, and its employees for the help and cooperation extended to Cottrell Environmental Sciences in conducting the pilot test activities at the Comanche Station. We also wish to thank Theodore G. Brna, EPA Project Officer, for his aid and direction in carrying out this program. Financial support for the program provided by the Department of Energy by means of an interagency transfer of funds to the United States Environmental Protection Agency is gratefully acknowledged.

SECTION 1

INTRODUCTION

Dry SO_2 scrubbing has strongly emerged as a new technology and appears to be a cost-effective desulfurization process for low sulfur, western coals. Contracts for at least ten of first generation dry scrubbing systems already have been awarded and many additional projects are being evaluated. The attractiveness of the dry SO_2 scrubbing system compared to wet FGD lies in its physical simplicity, moderate pressure drop, very low water use, reduced reheat requirements and in the dry condition of the reduced volume of waste solids produced.

The first example in the United States of dry SO_2 scrubber testing using a spray dryer for utility coal-fired boiler application is the Rockwell International investigation in the early 1970's (1-1). A spray dryer was used to remove SO_2 with an aqueous sodium carbonate reagent. However, major spray dryer SO_2 scrubbing test activity began only as recently as 1977. At this time, several companies (Babcock & Wilcox, Carborundum, Joy-Niro and Rockwell International) participated in spray drying and baghouse pilot testing at the Leland Olds Station of Basic Electric Power Cooperative. Sodium reagents were tested initially but potential disposal problems and high costs turned the investigations toward other alkaline compounds. Additional testing indicated that slaked lime held the most promise as an economical reagent for dry SO_2 scrubbing.

Joy-Niro (1-2) conducted pilot tests at the Hoot Lake Station of Otter Tail Power Company in which greater than 90 percent overall SO_2 removal was accomplished at a stoichiometric ratio of 2.0 to 3.0 moles lime/mole SO_2 using lime-only operation and at 1.0 to 1.5 moles lime/mole SO_2 with recycle. The study also identified the importance of operating the spray dryer near the adiabatic saturation temperature to enhance SO_2 removal. The Hoot Lake results also showed that an alkaline flyash, especially under recycle operation, contributes significantly to SO_2 removal.

Babcock & Wilcox (1-3) field and laboratory pilot tests utilizing a horizontal flow reactor and dual fluid atomization identified several variables that affect SO_2 removal. They include stoichiometry, approach to adiabatic saturation temperature, inlet gas temperature to the system, and flyash alkalinity. Lime stoichiometry was the primary correlating variable with SO_2 removal, but flyash alkalinity also played a strong role. SO_2 removal using flyash alone ranged from about 15 percent to as high as 65 percent with highly alkaline Laramie River flyash.

Buell/Anhydro (1-4) parametric pilot tests at the Martin Drake Station of the City of Colorado Springs showed the importance of operating near the adiabatic saturation temperature on SO_2 removal but found that inlet gas temperature to the spray dryer had a negligible effect. Using lime-only operation, SO_2 removal was found to be considerably reduced at 2000 and 2500 ppm inlet SO_2 concentrations from that at 1000 and 1500 ppm SO_2. Fabric filter SO_2 removal in the Martin Drake tests was strongly affected by the approach to adiabatic saturation temperature and was also a function of stoichiometric ratio.

The present program examines the applicability of dry SO_2 scrubbing technology to treat utility flue gas using a spray dryer and fabric filter. A pilot test program at the Comanche Station of Public Service Company of Colorado investigates the effect of key process variables on SO_2 removal. Study of the fabric filter variables on SO_2 removal is confined to the effects that take place simultaneously with the testing of the spray dryer. Also, the present investigation does not address the efficiency of particulate removal in the dry scrubbing system.

The final phase of the field test program is a continuous demonstration of spray dryer/fabric filter technology. The demonstration run is to verify that SO_2 removal can be achieved on a sustained basis to meet the New Source Performance Standards (NSPS) for utility boilers operating on flue gas generated from low sulfur fuels. Field test results are utilized in a techno-economic evaluation to establish the areas where dry FGD technology may be applied economically.

The characteristics of the solid wastes produced from the dry SO_2 scrubbing system are also evaluated. Materials generated at the pilot test site are examined at the CES laboratory facilities. This limited scope program of testing and evaluation is to determine 1) the basic composition of the waste products and 2) the soil-mechanical and leaching properties of the FGD solids/flyash mixtures. Solids samples are also analyzed for trace heavy metals to provide hazardous waste information.

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SECTION 2

CONCLUSIONS

MAJOR PROCESS VARIABLE STUDIES

Spray Dryer SO_2 Removal

1. The process parameters that dominate spray dryer SO_2 removal performance are:

   - Stoichiometric Ratio
   - Approach To Adiabatic Saturation Temperature
   - Temperature Drop Across the Spray Dryer
   - Recycle Ratio

2. Spray dryer SO_2 removal increases directly with fresh lime stoichiometry. At the lower stoichiometries, SO_2 removal the in spray dryer is quite sensitive to stoichiometric ratio. At the higher stoichiometries, SO_2 removal tends to level off so that the stoichiometric ratio has much less effect on spray dryer SO_2 removal.

3. SO_2 removal efficiency in the spray dryer increases as the flue gas temperature approaches the adiabatic saturation temperature.

4. SO_2 removal in the spray dryer increases as the temperature drop across the spray dryer is increased. Spray dryer temperature drop directly reflects the liquid-to-gas ratio and the quantity of water fed to the dryer.

5. Spray dryer solids moisture content increases as the flue gas temperature approaches the adiabatic saturation temperature.

6. The optimum spray dryer operating temperature strikes a balance between high SO_2 removal and smooth trouble-free discharge and handling of moisture-laden product solids.

7. Spray dryer SO_2 removal is enhanced as the amount of recycle material (recycle ratio) increases. SO_2 removal increases as recycle ratio increases up to a value of about 2.5 lb recycle solids/lb fresh lime where it levels off indicating no further benefit to recycling additional solids.

8. For a lime-only (no recycle) mode of operation, spray dryer SO_2 removal appears to increase slightly, if at all, with increasing spray dryer

TYPING GUIDE SHEET

residence time in the range investigated (8 to 16 sec). Spray dryer flue gas residence time has no significant effect on SO_2 removal when operating under recycle conditions.

9. Spray dryer inlet SO_2 concentration has very little effect on SO_2 removal.

Fabric Filter SO_2 Removal

1. The process parameters that significantly affect fabric filter SO_2 removal are:

   o Stoichiometric Ratio
   o Approach to Adiabatic Saturation Temperature
   o Recycle Ratio

2. SO_2 removal in the fabric filter increases proportionately with increasing fresh lime stoichiometry.

3. SO_2 removal in the fabric filter increases as the flue gas temperature approaches the adiabatic saturation temperature.

4. Product solids recycle enhances SO_2 removal across the fabric filter.

5. Solids moisture content in the fabric filter increases as the flue gas temperature approaches the adiabatic saturation temperature.

6. The optimum fabric filter operating temperature is low enough to achieve good SO_2 removal but high enough to avoid operating and/or materials handling problems that result from excessive moisture content.

7. Air-to-cloth ratio has a negligible effect on SO_2 removal in the fabric filter.

8. Fabric filter inlet SO_2 concentration has no significant effect on fabric filter SO_2 removal.

9. Fabric filter SO_2 removal increases as the pressure drop across the fabric filter increases during an operating cycle.

Overall SO_2 Removal

1. The dry scrubbing system is capable of attaining 70 to 90 percent SO_2 removal required by the New Source Perfromance Standards (NSPS). Lime stoichoimetry is minimized by operating with recycle at high flue gas inlet temperature to the spray dryer, low spray dryer outlet temperature and low fabric filter inlet temperature.

2. The spray dryer is the primary SO_2 control unit in the system while the fabric filter is the primary particulate control unit. In the present study, more than 75 percent of the total SO_2 removal occurred in the spray dryer and considerably greater than half of the total solids collection took place in the fabric filter.

3. The general effects and trends of the process parameters on SO_2 removal are similar for lime-only and recycle operating modes.

SPRAY DRYER ATOMIZER VARIABLES

1. Slightly greater spray dryer SO_2 removal in combination with significantly higher moisture content product solids are produced at a low atomizer speed (10,600 rpm) than at higher atomizer speeds (12,360 and 13,920 rpm).

2. An atomizer wheel containing six 5/16 in. diameter ports produces better spray dryer SO_2 removal than a wheel containing 80 1/8 in. wide slots on its periphery.

3. No significant difference in SO_2 removal occurs between a flue gas distributor vane producing gas flow co-rotational to the atomizer slurry and one producing flow counter-rotational to the atomizer slurry.

LIME SLAKING

1. A slight variation in SO_2 removal is experienced with lime slaking temperatures between 165°F and 190°F but the reason is not clear.

2. No significant difference in spray dryer SO_2 removal occurs using water of three different qualities for lime slaking: normal tap water, boiler blowdown water, and high (1260 ppm $SO_4^=$) sulfate water.

3. No significant difference in spray dryer SO_2 removal is obtained employing three different sources of lime: Peter Lien (South Dakota), Ash Grove (Missouri), and Salida (Colorado).

4. Lower slaker speed produces greater spray dryer SO_2 removal in the pilot plant spray dryer.

PROCESS DEMONSTRATION

1. A 5-day, 120-hour, continuous process demonstration run was successfully conducted without interruption and with negligible operating problems.

2. The continuous run demonstrates that the spray dryer/fabric filter system is able to consistently achieve the 70 percent SO_2 removal level required to meet the New Source Performance Standards for low sulfur coal.

PRODUCT SOLIDS CHARACTERIZATION

1. Product solids collected in the spray dryer are coarser than those collected in the fabric filter. Spray dryer product solids mean diameter is 30 to 35 µm compared to fabric filter mean diameter of about 10 µm.

2. Particle size distributions of the fabric filter solids approximate those of Comanche flyash itself.

3. The split of collected solids betweeen the spray dryer and fabric filter is a function of system operating parameters as reflected by the spray dryer solids moisture content. The fraction of total solids collected in the spray dryer increases as the moisture content of the spray dryer solids increases.

4. Product solids collected in the spray dryer contain more moisture than those collected in the fabric filter.

5. For a given run, spray dryer and fabric filter solids contain about the same fly ash concentration. Spray dryer solids generally contain more reagent compounds; fabric filter solids generally contain more FGD product solids.

PRODUCT SOLIDS REACTIVITY

1. The source of the recycled solids has a negligible effect on SO_2 removal. Recycling spray dryer solids, fabric filter solids or a mixture of both produces essentially similar results.

2. Continuous ball milling of recycle solids for an average residence time of 30 minutes has no significant effect on SO_2 removal.

3. Slurried Comanche flyash (Powder River Basin Coal) alone (no fresh lime) removes 30 percent SO_2 from the flue gas at an available alkalinity of 1.5 moles alkali/mole SO_2. The percentage of SO_2 removal correlates linearly with the potentially available alkalinity of the flyash.

4. Slurried recycled product solids alone (no fresh lime) removes about 15 percent SO_2 at a stoichiometry of 1.0 moles lime/mole SO_2. SO_2 removal correlates well with the available alkalinity of the solids.

WASTE CHARACTERIZATION STUDY

1. Optimum compacted densities of 78 to 90 lb/ft^3 are obtained at dry waste solids moisture contents of 25 to 35 wt. percent H_2O. Dry scrubbing waste product compacted densities are lower and corresponding moisture contents are higher than values reported for sludge/flyash blends from wet FGD systems (115 to 120 lb/ft^3 and 15 to 20 wt. percent H_2O).

2. The cohesive strength and angle of internal friction of waste products from the lime-only runs are 40 to 50 percent greater than the values measured for the waste products from recycle runs. Cohesive strength increases 3 to 10 fold and angle of internal friction increases 30 to 50 percent upon curing of waste solids for approximately one month at $72^{\circ}F$ and $\sim$ 100 percent relative humidity.

3. Permeability values for uncured dry scrubbing product solids are of the order of 10^{-5} cm/sec. For samples cured approximately one month at $72^{\circ}F$ and $\sim$ 100 percent relative humidity, permeability values are in the range of 10^{-6} to 10^{-7} cm/sec.

4. The total dissolved solids (TDS) content of the leachate from the dry scrubbing waste products generally exceeds 1200 ppm; most of the TDS is attributable to $CaSO_4$.

TECHNOECONOMIC EVALUATION

1. The capital investment required for a dry SO_2 scrubbing system (spray dryer/fabric filter) is 30 to 35 percent less than that required for either of two wet FGD systems examined (fabric filter/limestone scrubber, ESP/limestone scrubber) based on estimates for a 500 MW unit burning Powder River Basin Coal containing 0.6 percent sulfur and complying with the NSPS.

2. Direct capital costs for the dry SO_2 scrubbing system are lower than for the wet scrubbing systems in five of six major process areas: feed preparation, gas handling, SO_2 absorption, particulate removal, and waste disposal. Only materials handling direct costs are higher for the dry scrubbing system than for the wet scrubbing systems.

3. Annual operating costs (first year annual revenues) for a dry SO_2 scrubbing system (spray dryer/fabric filter) are 25 to 30 percent lower than for either of the two wet scrubbing systems (fabric filter/limestone scrubber, ESP/limestone scrubber).

4. Reagent costs for a dry scrubbing system utilizing lime are much higher than for wet scrubbing systems utilizing limestone. Lime costs 4 to 5 times as much as limestone for SO_2 control of a system burning 0.6 wt. percent sulfur coal and is a major operating expense for dry scrubbing systems. Lime reagent cost is affected by coal sulfur content, stoichiometric ratio, and raw materials price.

5. Unit capital costs ($/kW) are only moderately sensitive to system size (MW) for all three types of systems. Unit capital costs increase as coal sulfur content increases. Dry scrubbing systems costs are more sensitive to coal sulfur content than are wet scrubbing system costs.

6. For each of the three desulfurization processes, unit operating costs (mills/kWh) decrease as system size (MW) increases but are not very sensitive to size. Unit operating costs increase as coal sulfur content increases because of increased reagent usage. Dry scrubbing system operating costs are more sensitive to coal sulfur content than are limestone wet scrubbing system operating costs because dry systems utilize expensive lime as the reagent.

7. As coal sulfur content increases, the cost advantage of a dry system over a wet system decreases. The crossover range is about 1.5 to 1.8 percent sulfur for the conditions used in the present study.

SECTION 3

DRY SO_2 SCRUBBING PILOT SYSTEM

PILOT SYSTEM DESCRIPTION

The pilot test system (see Figures 3-1 and 3-2) is designed to treat up to 10,000 acfm[1] (nominal) of flue gas. The system consists of a spray dryer to remove SO_2 followed by a fabric filter to collect dry FGD solids and flyash. An induced draft fan moves the flue gas through the system and a second "reverse air" fan is used to clean the fabric filter. Feed tanks and metering pumps are provided to supply reagent to the system. An SO_2 tank and delivery system provide additional SO_2 to the flue gas for tests at higher inlet flue gas SO_2 concentrations. Ductwork and dampers for flue gas transport and diversion are part of the system. In keeping with normal pilot plant practice, most control is accomplished manually in order to maintain maximum operating flexibility. The unit is thoroughly instrumented to provide the necessary basis for control as well as to provide complete detailed data to define the performance of the unit.

Spray Dryer

The pilot spray dryer is an 8 ft diameter by 35 ft high unit equipped with a variable speed rotary disc atomizer. The atomizer type used in this test program has a titanium body with silicon carbide ports inserted around the periphery of the disc. The bottom plate of the titanium disc is coated with aluminum oxide for protection against slurry abrasion.

Dirty flue gas containing SO_2 and flyash enters the top of the spray dryer where it is intimately contacted with finely atomized lime slurry. The temperature of the inlet flue gas to the spray dryer is controlled by flowing it through the air-to-flue gas cooler. For testing at higher inlet SO_2 concentrations, the flue gas is spiked at a point about 10 ft upstream of the spray dryer inlet with SO_2 from cylinders. SO_2 is injected at the center of the 20 in. diameter flue gas duct.

The intimate contact and large interfacial area provided by the spray dryer result in very rapid SO_2 absorption by the lime slurry. Most of the SO_2 removal in the overall system occurs in the spray dryer. Before leaving the

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[1] EPA policy is to express all measurements in Agency documents in metric units. This report uses English units which are customary in the U.S. to improve clarity of presentation. Conversion factors are provided in Appendix E.

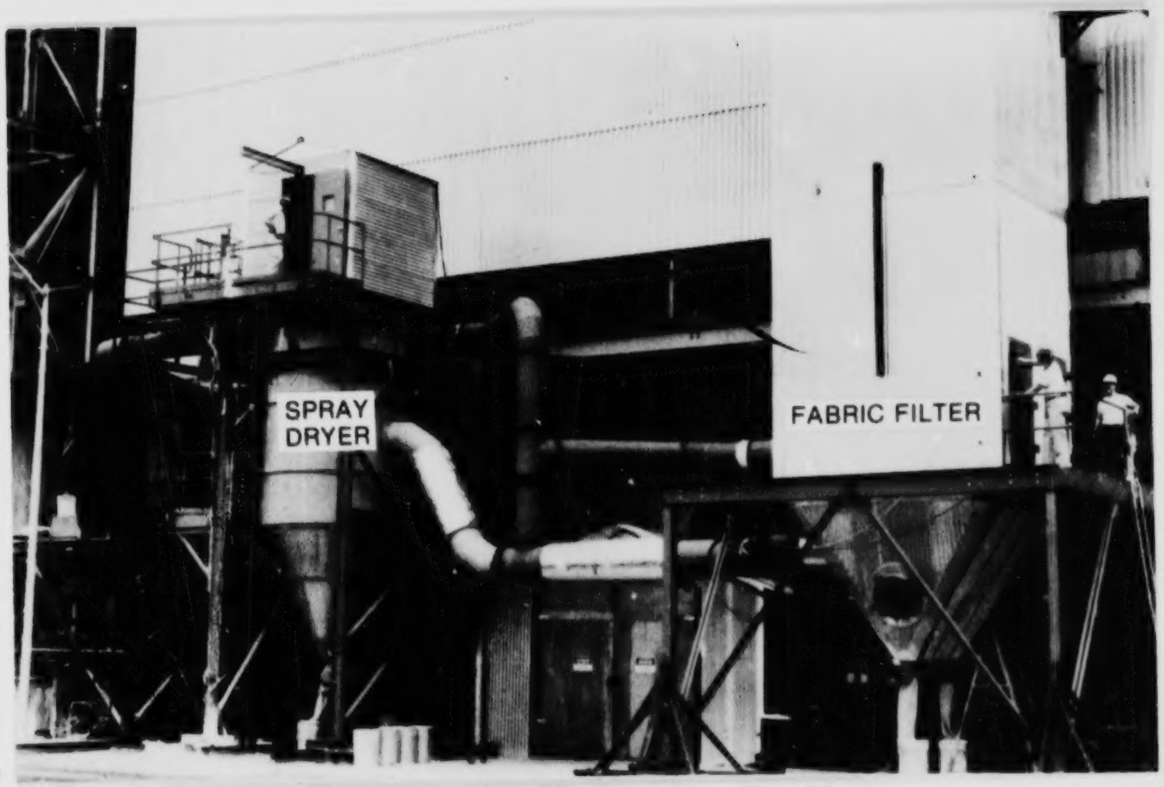

SPRAY
DRYER
FABRIC FILTER

Figure 3-1. Dry SO_2 Scrubbing Pilot Plant.

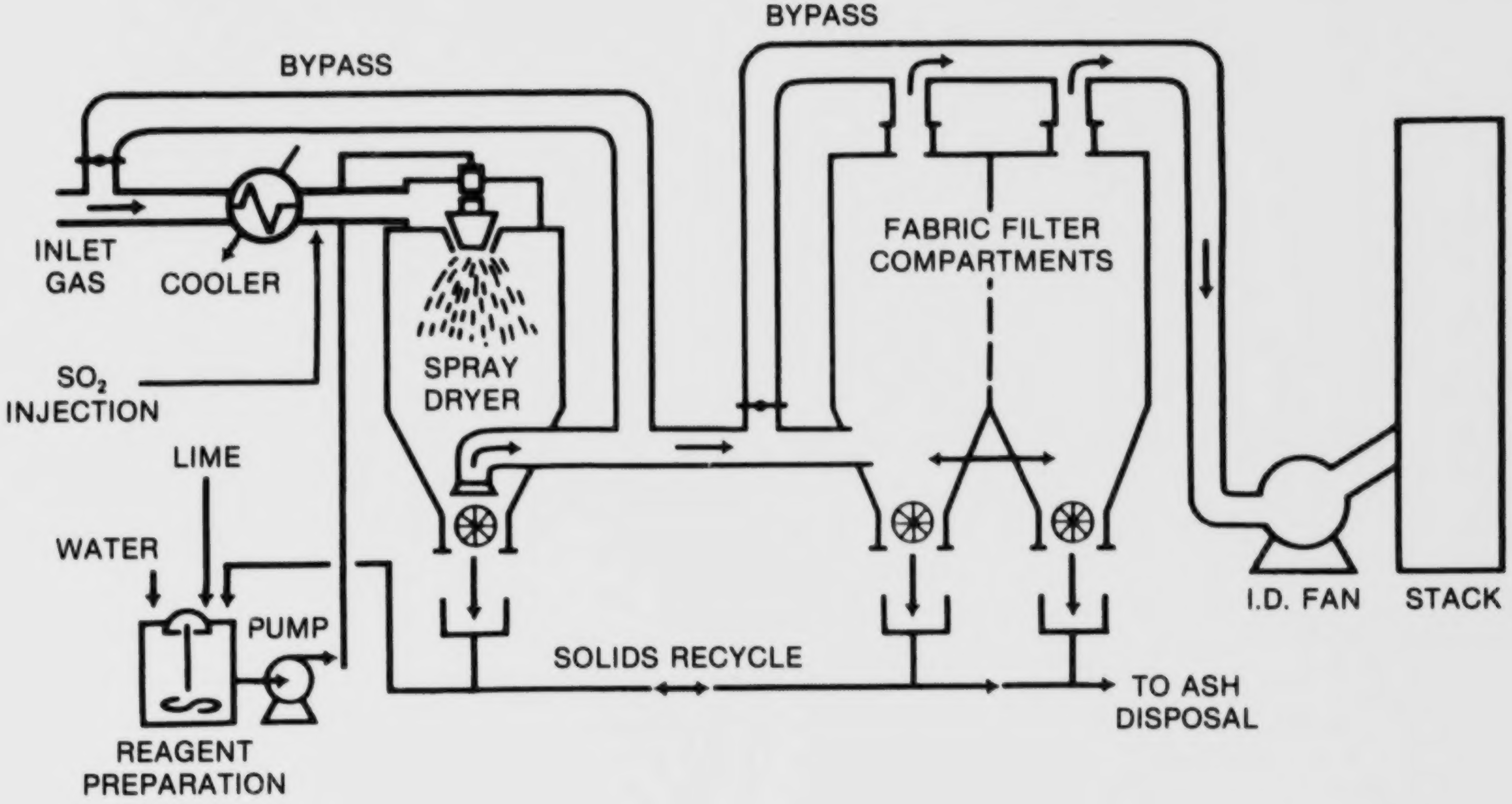

BYPASS
BYPASS
INLET GAS
COOLER
SO₂ INJECTION
SPRAY DRYER
FABRIC FILTER COMPARTMENTS
LIME
WATER
PUMP
REAGENT PREPARATION
SOLIDS RECYCLE
TO ASH DISPOSAL
I.D. FAN
STACK

Figure 3-2. Dry SO_2 Scrubbing Pilot Flow Schematic.

dryer, the solids approach complete dryness. In the pilot unit, coarse solids tend to settle in the conical bottom of the dryer and are discharged through a rotary valve to receiving drums. The scrubbed flue gas containing finer particles leaves the dryer through a side exit port and flows to the fabric filter. The construction of the spray dryer permits considerable flexibility in location of the gas outlet position and degree of solids removal as well as total contact time.

During testing, conditions are held at fixed values until the system operation responses, particularly sulfur dioxide removal efficiency and temperature drop, are accurately measured. Primary, quick response control of the spray dryer is obtained by varying the total lime feed rate and the total water feed rate. Temperature drop across the unit is controlled by total water flow to the unit. Water for temperature control is metered as trim water flow to a mixing tee immediately upstream of the spray dryer atomizer. System SO_2 responses to changes in stoichiometry are observed on a du Pont UV analyzer which samples both inlet and outlet gas streams from the spray dryer and fabric filter.

Fabric Filter

The fabric filter unit size is 10 ft x 15 ft x 55 ft and is operated with two compartments each designed to process about 5,000 cfm of flue gas. Commercial Teflon-coated fiberglass bags were employed in the fabric filter. Each of the fabric filter bags is 12 in. in diameter and 30 ft high and contains about 94 ft^2 of bag surface. Twenty to twenty-four bags (10 to 12 per compartment) were used in various tests throughout the pilot program.

In the fabric filter, flyash and FGD solid particulate are removed from the flue gas and additional SO_2 removal takes place. From the fabric filter, the flue gas flows to the I.D. fan and then to the stack. Flue gas from the spray dryer continuously enters the bottom of the fabric filter unit and leaves from the top.

To meet the requirement of high inlet temperature into the fabric filter (200°F) for the process demonstration test, hot ($\sim$ 400°F), dirty flue gas is by-passed around the cooler and the spray dryer. This by-passed gas is mixed with the gas exiting the dryer just prior to entering the filter. Hence, the gas mixture entering the fabric filter is hotter, drier, and has a higher SO_2 concentration than that exiting the spray dryer.

To limit pressure drop across the filter bags from the accumulation of collected solids, a flow of air periodically is passed through the bags in the reverse direction for a short period of time (1 to 2 minutes per hour). The "reverse air" flow causes most of the solids deposited to dislodge from the bag surface and drop into the collection hoppers where they are discharged through rotary valves. During the brief bag cleaning period, flue gas is bypassed around the fabric filter. Valve operation is accomplished from the control room either by manual valve direction or by use of an automatic sequencing system.

Slurry Feed System

Granular lime is fed from the lime bin to the lime Vibra-Screw feeder. The feeder sends the quick lime to the pugmill slaker where it is mixed and reacted with water. The hydrated lime slurry is diluted, degritted, and fed by gravity into the lime tank. The rate and concentration of lime slurry produced are controlled by adjusting the Vibra-Screw lime rate and the water rate to the slaker.

Normally plant tap water (softened river water) is used to slake the quicklime and dilute the slurry. In the case of the demonstration run, special dilution water was used which contained 25 wt. percent clarifier underflow plus 75 wt. percent chemically-doped water to simulate the cooling tower blowdown. Dilution water is supplied from a separate tank which contained the "synthetic" water mixture. The dilution water analysis is presented in Table 3.1

TABLE 3.1 DILUTION WATER COMPOSITION

Component	Value
Ca^{++}, ppm as $CaCO_3$	82
Mg^{++}, ppm as $CaCO_3$	432
Na^{+}, ppm as $CaCO_3$	24,520
$SO_4^{=}$, ppm as $CaCO_3$	21,200
Cl^{-}, ppm as $CaCO_3$	2,080
K^{+}, ppm as $CaCO_3$	9
TDS, ppm	41,920
TSS, ppm	525
pH	9.1

To maintain uniformity, lime slurry is recirculated around the lime tank by means of the lime pump. A bleed stream from this tank is metered and pumped directly to the spray dryer or to the recycle tank depending on the mode of operation.

Recycle Solids

Two different modes of recycle operation are used, one-tank and two-tank operation. In the one-tank mode of operation, the tank initially contains fresh lime slurry of known concentration. Product solids and dilution water are added to bring the mixture to a prescribed recycle ratio and total solids concentration. The combined slurry is then metered to the spray dryer. In the single tank mode, recycle ratio cannot be varied unless the mixed feed slurry composition is deliberately changed from its prescribed level.

In the two-tank mode, one tank contains only fresh lime slurry, and the other tank contains only a slurry of recycled product solids. Each slurry is metered to the spray dryer individually, and recycle ratio is varied by adjusting the respective flow rates.

No tests were performed to specifically determine the effect on SO_2 removal of using one-tank versus two-tanks for reslurrying recycle solids. The one-tank method was found more convenient for the process demonstration run described in Section 8, while the two-tank method was used for the remaining process variables tests. The two-tank mode for reslurrying recycle solids has the potential to produce more SO_2 removal than the one-tank mode because the alkalinity in the recycle solids (fly ash and FGD solids) is extracted to a greater degree into water than into a strongly alkaline aqueous lime slurry. As a result, the potentially available total alkalinity of lime and recycle solids is greater with the two-tank mode.

Upon mixing the lime slurry and recycle solids slurry from the two-tank operation, the alkaline species in the aqueous phase are expected to equilibrate rapidly and excess alkalinity precipitates from solution. However, the precipitated alkalinity probably is not reincorporated fully into the fly ash solids matrix. If the total alkalinity were now more readily available for reaction with SO_2, somewhat increased SO_2 removal would be expected from the two-tank mode over one-tank operation.

Flue Gas By-Pass

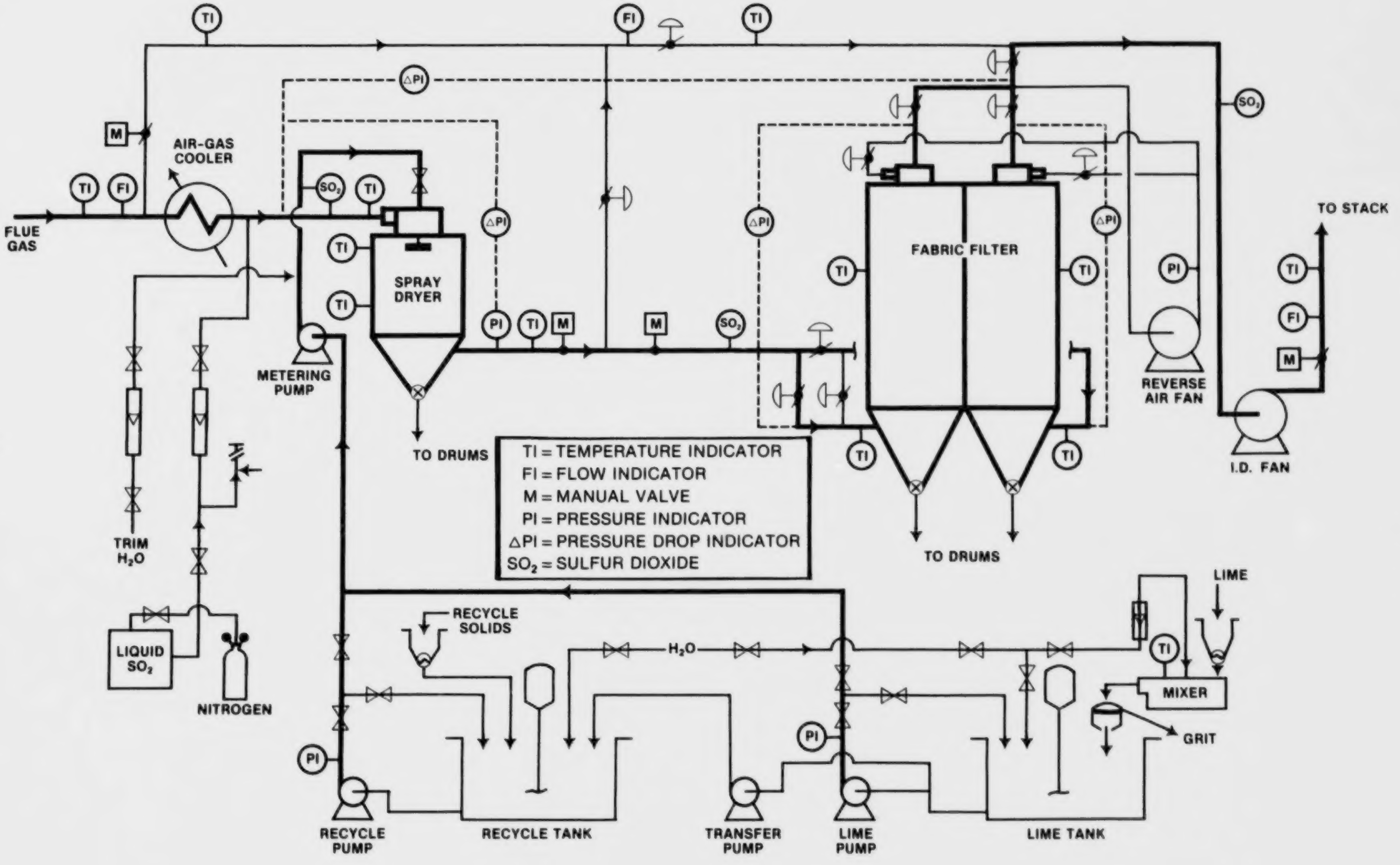
The process demonstration run was conducted using reheat of the flue gas exiting the spray dryer before it entered the fabric filter. Reheat of flue gas was required to maintain the fabric filter flue gas hot enough to avoid pressure drop increases from caking of moist solids. Flue gas reheat is accomplished by means of by-passing a portion of the hot flue gas around the cooler and spray dryer. Combining the by-pass flue gas with that from the spray dryer produces a mixture fed to the fabric filter with a higher temperature, higher SO_2 content, and lower moisture content than the spray dryer exit flue gas.

Instrumentation/Measurement

A description of the pilot test system measuring devices and instrumentation is presented in Table 3.2. Location of the measurement sensors in the spray dryer/fabric filter process is shown in Figure 3-3. Table 3.2 also shows the smallest graduated division (least count) for each measuring instrument. An observer generally is able to read to about one-half of the minimum division which provides an estimate of precision of the various instrument readings.

SO_2 Measurement--

At the relatively high levels of SO_2 concentration encountered in the flue gas fed to the spray dryer, the contributions to error are mainly measurement reading errors and general variations of the plant SO_2 level. SO_2 concentration sometimes changed by 10-15 ppm in several minutes time. At the spray dryer outlet and fabric filter inlet, the drift in the SO_2 recorder zero reading, although frequently checked and corrected, also added to SO_2 concentration measurement error. Error in SO_2 measurement, especially at low concentrations is the greatest factor affecting the accuracy of the results.


FLUE GAS
TI
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AIR-GAS COOLER
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ΔPI
SO₂
TI
SPRAY DRYER
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METERING PUMP
TO DRUMS
ΔPI
PI
TI
M
FI
M
TI
ΔPI
SO₂
FABRIC FILTER
TI
TI
TI
TI
ΔPI
TO DRUMS
PI
REVERSE AIR FAN
SO₂
TO STACK
TI
FI
M
I.D. FAN
TRIM H₂O
LIQUID SO₂
NITROGEN
TI = TEMPERATURE INDICATOR
FI = FLOW INDICATOR
M = MANUAL VALVE
PI = PRESSURE INDICATOR
ΔPI = PRESSURE DROP INDICATOR
SO₂ = SULFUR DIOXIDE
RECYCLE SOLIDS
H₂O
LIME
TI
MIXER
GRIT
PI
PI
RECYCLE PUMP
RECYCLE TANK
TRANSFER PUMP
LIME PUMP
LIME TANK

Figure 3-3. Spray Dryer/Fabric Filter Process Flow Diagram.

TABLE 3.2 INSTRUMENT DESCRIPTION AND PRECISION

Item	Description	Measurement	Minimum Instrument Gradation
Dry Bulb Temperature	All dry bulb measurements are made by thermocouple and are connected to a multi-point recorder.	Process Temperature Cooler Inlet Temperature	5°F 10°F
Wet Bulb Temperature	Water-saturated wick (gauze) covering a thermometer bulb positioned in the flue gas streams measures wet bulb temperature.	Adiabatic Saturation Temperature	1°F
Pressure	Magnahelic gages are used to measure all gas phase pressure drops.	Pressure Drop: System Dryer Baghouse	0.5 in. H_2O 0.2 in. H_2O 1 in. H_2O
SO_2	Sulfur dioxide concentration is measured by a du Pont SO_2 analyzer in three locations: gas inlet, gas to stack, and gas exit from spray dryer.	Calibration @ 800 ppm	10 ppm
Gas Flow Rate	Gas flow and blow back through baghouses are controlled by a series of dampers. Calibration by "Annubar" Type S averaging pitot.	Orifice Meters with Slant Tube	0.02 in. H_2O
Liquid & Slurry Flow Rates	H_2O via rotameters. SO_2 from tank via rotameter. Slurry flow via Moyno metering pumps	Water Rotameter Moyno Pump Settings: Small Medium Large	0.05 gpm 0.5 Division 0.5 Division 0.2 Division
Solids Flow Rate	Catch, time and weigh	Toledo Scale and 55 Gal Drum	¼ lb.
O_2/CO_2	Oxygen & carbon dioxide concentrations in the flue gas are measured via Orsat analysis; O_2 measurement is also performed by a Beckman paramagnetic analyzer.	Oxygen/CO_2	0.5%
Slurry/ Solids Analyses	Product solids and spray dryer feed slurry properties: Moisture content, Specific Gravity; Wt.% $Ca(OH)_2$	Analytical Balance (weight) Graduated Cylinder (50 ml) Ohaus Balance	0.001 gm 1 ml 1 %

Lime and Recycle Solids Slurry Feed Rate--

Smooth calibration curves of the pump discharge rate vs. pump setting were established for each of the Moyno pumps used in the pilot plant study. The pumps were checked for calibration at the beginning of each monthly test program segment. In general the ability to measure lime slurry feed rates was good, except at the lowest flow rates using the smallest Moyno pump.

Adiabatic Saturation Temperature--

The estimated precision of the measurement of the adiabatic saturation temperature using a wick and glass thermometer is ± 0.5°F.

Solids Moisture Content--

Samples of solids collected from the spray dryer and fabric filter discharges were analyzed by evaporating to dryness using an IR lamp and Mettler analytical balance. Precision is estimated at less than ± 0.1 percent absolute value of percent moisture.

Recycle Ratio--

Recycle solids/lime slurry feed was prepared, in the single tank mode of operation, by weighing in amounts of recycle solids and lime slurry of known lime content to provide a batch mixture for several hours of continuous testing. Recycle ratio was initially estimated for the tests from the weights of the recycle solids and the lime slurry. Numerical values of recycle ratio were later calculated during the data analysis from the actual analysis of percentage solids and percentage $Ca(OH)_2$ in samples of the composite feed slurry.

The major source of control error in recycle ratio preparation estimates in the single tank mode is the relatively rough measurement of the weight of large, (i.e., 55 gal. drum) quantities of recycle solids which is estimated at ± 10 percent. The actual calculated and reported values are good to ± 5 percent relative.

In the two-tank mode of operation, recycle ratio is controlled by flow rate adjustments of the makeup lime and recycle solids slurries by means of the Moyno pumps. The error in recycle ratio determination is related to slurry compositions and to Moyno feed rate control and is estimated at less than ± 5 percent.

SECTION 4

PILOT TEST PROGRAM

The overall objective of the dry SO_2 scrubbing test program is to define the applicability of dry SO_2 scrubbing technology to treat utility flue gas using a spray dryer and fabric filter. This objective is accomplished by means of an in-depth field test program which investigates the effect of key operating variables on SO_2 removal. The pilot test program consists of two parts: process variable parametric studies and a continuous process demonstration run. FGD solids/fly ash samples collected at the Comanche test site during the pilot runs were used for the laboratory waste characterization studies.

Process Variable Tests

The process variable tests were empirical investigations designed primarily to identify the dominant variables that affect SO_2 removal and to establish their relative importance rather than to determine why they are important or the underlying mechanisms involved. The parametric studies were carried out employing two operating modes:

- Process variable tests using lime reagent in once-through operation with no product solids recycle. Key spray dryer and fabric filter process variables were studied to establish their relative importance with respect to SO_2 removal. Additional continuous tests were conducted to define further the effects of the operating variables and to test different atomizer discs. The pilot tests were conducted either in 12-16 hour shifts/day or in "around-the-clock" operation.

- Process variable tests incorporating recycled solids. Continuous process variable tests utilizing solids recycled from the spray dryer and fabric filter were carried out to remove SO_2 with improved lime reagent utilization.

The process variables considered relevant to SO_2 removal that were investigated for the spray dryer and fabric filter are presented in Table 4.1. These parameters were studied over the ranges of conditions shown in Table 4.2. Numerous additional operating conditions were observed and recorded during the pilot tests to assure controlled test operation.

TABLE 4.1 VARIABLES INVESTIGATED

Spray Dryer

- Lime/SO_2 Stoichiometry
- Inlet Gas Temperature
- Outlet Gas Temperature
- Inlet Gas SO_2 Concentration
- Flue Gas Rate (Residence Time)
- Atomizer Speed
- Lime Slaking Conditions
- Solids Recycle

Fabric Filter

- Lime/SO_2 Stoichiometry
- Flue Gas Temperature
- Recycle Ratio
- Air-to-Cloth Ratio
- Inlet Gas SO_2 Concentration
- Pressure Drop

TABLE 4.2 RANGE OF PILOT TEST VARIABLES

Variable	Minimum	Maximum
Stoichiometric Ratio, moles $Ca(OH)_2$/mole SO_2 inlet	0.5	6.4
SD Inlet Flue Gas Temperature, °F	226	340
SD Outlet Flue Gas Temperature, °F	128	210
SD Adiabatic Saturation Temperature, °F	111	130
Inlet SO_2 Concentration, ppmv	185	2150
Atomizer Disc Diameter, in.	7-3/8	8-1/2
Atomizer Disc Speed, rpm	10,600	13,920
Inlet Flue Gas Rate, acfm	3,000	7,500
Fabric Filter Air-to-Cloth Ratio, ft/min.	1.3	2.8
Fabric Filter Gas Temperature, °F	117	200
Lime Slurry Feed Concentration, wt.%	3	25
Recycle Slurry Solids Concentration, wt.%	10	53
Recycle Ratio, lb recycle solids/lb fresh lime	0	4.3

Atmospheric pressure at the Comanche Station (4900 ft elevation) ranged from 24.5 to 25.5 in. Hg over the course of the dry SO_2 scrubbing test program.

Process Demonstration

A continuous process demonstration run was conducted to verify that SO_2 removal levels can be achieved on a sustained basis to meet New Source Performance Standards. Selection of the specific operating conditions for the demonstration was made based on the results of the process variable tests. Dry scrubbing system operability and control as well as SO_2 performance were observed over the course of the demonstration run.

SECTION 5

MAJOR PROCESS VARIABLE STUDIES

SPRAY DRYER SO_2 REMOVAL

Process Chemistry

The basic process chemistry of dry SO_2 scrubbing is fairly complex and involves a considerable number of reaction steps. The most important reaction is between sulfur dioxide and slaked lime to produce calcium sulfite. The calcium sulfite formed is partially oxidized to calcium sulfate by oxygen from the flue gas. A portion of the lime also reacts with the carbon dioxide present in the flue gas to form calcium carbonate. The main reaction products of lime are the solid compounds analyzed as $CaSO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$ and $CaCO_3$. The key overall reactions can be written as:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O \qquad (5\text{-}1)$$

$$CaSO_3 + \tfrac{1}{2}O_2 \rightarrow CaSO_4 \qquad (5\text{-}2)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (5\text{-}3)$$

In the spray dryer, flue gas containing SO_2 is energetically and intimately mixed with finely atomized lime slurry droplets. The spray dryer is designed for a very short contact time in which rapid evaporation of water from the slurry droplets occurs simultaneously with SO_2 absorption and reaction. The loss of water is characterized by an initial period of constant evaporation rate followed by a period of falling rate. During the constant rate period, evaporation of water proceeds as the free, or unbound, moisture escapes from the slurry droplet. At the end of the constant rate period, the solid particle surfaces cease to be fully wet with water. During the falling rate period, the evaporation rate slows down because the surface of the slurry particles is less than completely saturated. Evaporation rate continues to decrease as the moisture content of the FGD solids/fly ash agglomerates approaches a value that is in equilibrium with the flue gas at the prevailing temperature, pressure and humidity.

Dry Scrubbing Models

Simple mathematical models have appeared in the literature to describe dry scrubbing SO_2 removal (5-1). A model developed for the case of gas phase resistance controlling the SO_2 reaction rate is

$$\ln (1-\varepsilon_{SD}) = -K_1 \ln \frac{T_{IN/SD} - T_{AS/SD}}{T_{OUT/SD} - T_{AS/SD}} \qquad (5\text{-}4)$$

where ε_{SD} = spray dryer SO_2 removal fraction

K_1 = parameter that includes dimensionless ratios related to gas phase heat and mass transfer.

$T_{IN/SD}$ = flue gas spray dryer inlet temperature, °F

$T_{OUT/SD}$ = flue gas spray dryer outlet temperature, °F

$T_{AS/SD}$ = flue gas approach to adiabatic saturation at spray dryer outlet, °F

K_1 is nearly constant and a value of 0.62 was estimated for the range of dry SO_2 scrubber operating conditions of interest. This model relates SO_2 removal to the key temperature parameters in the spray dryer and is independent of stoichiometric ratio.

A second model presented by Downs et al. assumes that SO_2 removal is simply proportional to the lime reagent surface area. This model is given by

$$\ln (1-\varepsilon_{SD}) = -K_2\ SR \qquad (5\text{-}5)$$

where K_2 = parameter containing system variables held constant.

SR = stoichiometric ratio, moles lime/mole SO_2

The model describes SO_2 removal (ε_{SD}) under conditions where the SO_2 concentration is large enough (or constant) compared to available lime so that it does not affect the reaction rate.

These mathematical models reflect conditions at the extremes of SO_2 availability for reaction. The model of Eq. (5-4) holds at conditions when the SO_2 concentration at the reaction sites is so low that it limits the reaction. On the other hand, the model of Eq. (5-5) holds when the SO_2 concentration is so large that only lime reagent availability dictates the rate of reaction. Since the reaction conditions continually change in a complex way throughout the spray dryer, neither of the simple models presented is expected to alone fully describe SO_2 removal. However, the two models identify the key spray dryer variables that influence SO_2 removal--$T_{IN/SD}$, $T_{OUT/SD}$, $T_{AS/SD}$ and SR.

Process Variables

A limited number of process variables were found to control SO_2 removal in the spray dryer. The variables include:

- Stoichiometric Ratio
- Temperature Approach to Adiabatic Saturation
- Spray Dryer Temperature Difference

- o Recycle Ratio

These key process variables and a number of less influential process parameters were investigated employing lime-only (no recycle) and recycle modes of operation. The effects of these variables on spray dryer SO_2 removal are discussed in this section.

Range of Variables

Lime-Only

A series of pilot plant tests (103 runs) was conducted to examine the effect of the spray dryer process and system variables on spray dryer SO_2 removal for a once-through (no recycle) mode of operation. The variables and the ranges investigated in the field tests are presented in Table 5.1.

TABLE 5.1 RANGE OF SPRAY DRYER VARIABLES INVESTIGATED

LIME-ONLY OPERATION

Variable	Minimum	Maximum
Stoichiometric Ratio, moles $Ca(OH)_2$/mole SO_2 inlet	0.56	5.90
Approach to Adiabatic Saturation Temperature, °F	15	80
Spray Dryer Temperature Drop °F	80	200
Spray Dryer Residence Time, sec	8.1	16.4
Inlet SO_2 Concentration, ppm	200	2,150
Atomizer Disc Speed, rpm	13,920	

The detailed operating conditions and results of these 103 runs appear in Appendix A.

Recycle

A total of 96 runs was conducted under recycle conditions to investigate the effects of these external process variables. The matrix of tests encompassed a wide range of operating conditions as indicated in Table 5.2.

TABLE 5.2 RANGE OF SPRAY DRYER VARIABLES INVESTIGATED

RECYCLE OPERATION

Variable	Minimum	Maximum
Stoichiometric Ratio, moles $Ca(OH)_2$/mole SO_2 inlet	0.7	6.4
Approach to Adiabatic Saturation Temperature, °F	16	69
Spray Dryer Temperature Drop, °F	73	185
Recycle Ratio, lb recycle solids/lb fresh lime	0.45	4.28
Spray Dryer Residence Time, sec	8.4	15.8
Inlet SO_2 Concentration, ppm	185	2040
Atomizer Disc Speed, rpm	13,920	

The detailed operating conditions and results of these 96 tests appear in Appendix A.

Stoichiometric Ratio

Stoichiometric ratio is defined as the moles of fresh $Ca(OH)_2$ feed per mole SO_2 in the gas entering the system. Stoichiometric ratios are reported on an active or available slaked lime basis and are equivalent to 97 percent of the SR values arrived at employing the total weight of the slaked lime fed. Available slaked lime, $Ca(OH)_2$, is determined by titration with 1 N HCl to a phenolphthalein end point.

Lime-Only

As shown in Figure 5-1, lime stoichiometry significantly affects SO_2 removal. The percent SO_2 removal achieved in the spray dryer increases directly with stoichiometric ratio. Increasing the stoichiometric ratio from 0.6 to 3.0, at otherwise constant conditions, increases SO_2 removal in spray dryer from 25 percent to 50 percent. The percent SO_2 removal in the spray dryer, even at high stoichiometry, is only about 50 percent because the runs selected for study were at a temperature far above the adiabatic saturation ($\Delta T_{AS} = 60^{\circ}F$) where SO_2 removal is more limited. Table 5.3 presents the tabulation of key process conditions for the results in Figure 5-1.

TABLE 5.3 EFFECT OF STOICHIOMETRIC RATIO ON SPRAY DRYER SO_2 REMOVAL

Run No.	Stoichiometric Ratio (Moles Lime/ Mole SO_2 inlet)	Approach To Adiabatic Saturation ($^{\circ}F$)	Spray Dryer Temperature Difference ($^{\circ}F$)	Spray Dryer SO_2 Removal (%)
108	2.51	58	119	53.6
109	1.28	62	119	40.6
201	2.98	80	121	50.8
205	1.77	65	116	41.0
601	0.98	59	118	32.7
801	0.64	57	122	25.4
802	1.04	57	123	33.1
803	1.54	61	121	36.3
804	1.97	59	122	42.8
805	1.08	58	122	31.0
813	1.68	57	124	41.9
814	1.93	59	121	35.8
817	0.96	59	122	32.3
818	1.52	64	122	40.2
819	2.18	58	120	42.7
820	1.06	59	118	34.8
822	1.51	60	121	34.5
823	1.01	63	116	28.0

Recycle

As shown in Figures 5-2 through 5-4, the stoichiometric ratio significantly affects SO_2 removal under recycle operation. At stoichiometric ratios of less than 1.0, SO_2 removal increases linearly with stoichiometric

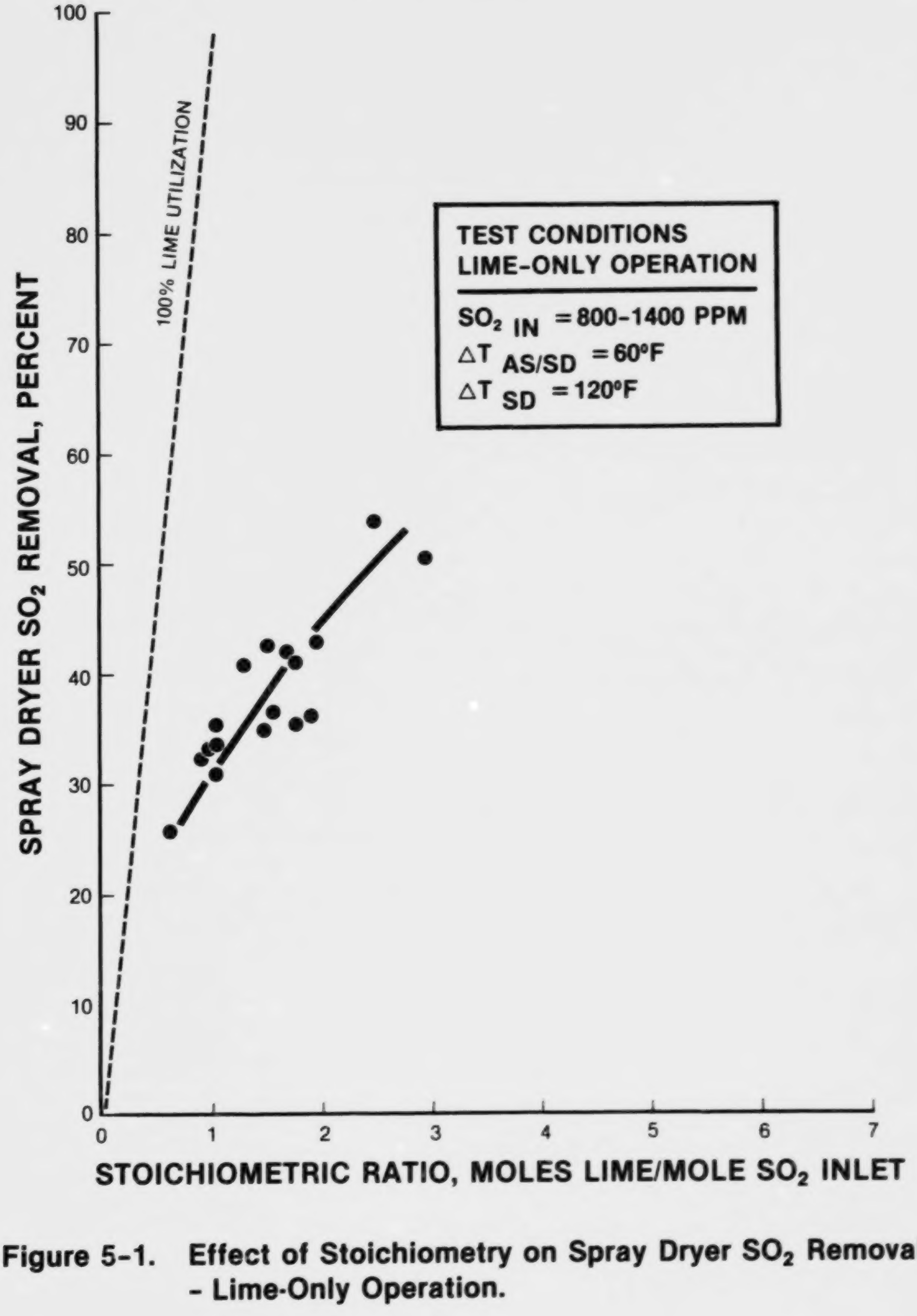


Figure 5-1. Effect of Stoichiometry on Spray Dryer SO_2 Removal - Lime-Only Operation.

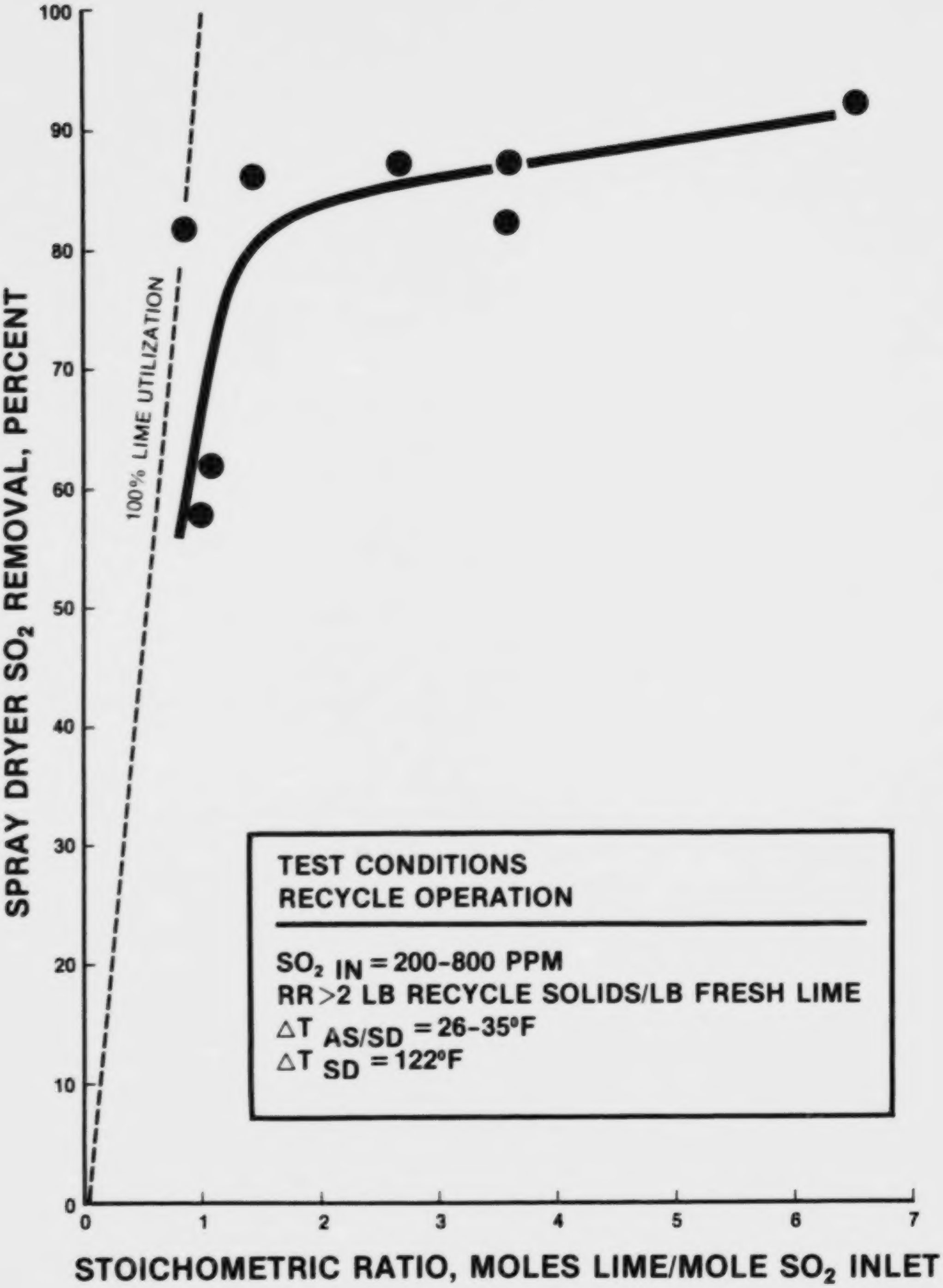


Figure 5-2. Effect of Stoichiometry on Spray Dryer SO_2 Removal at Moderate Spray Dryer Temperature Drop.

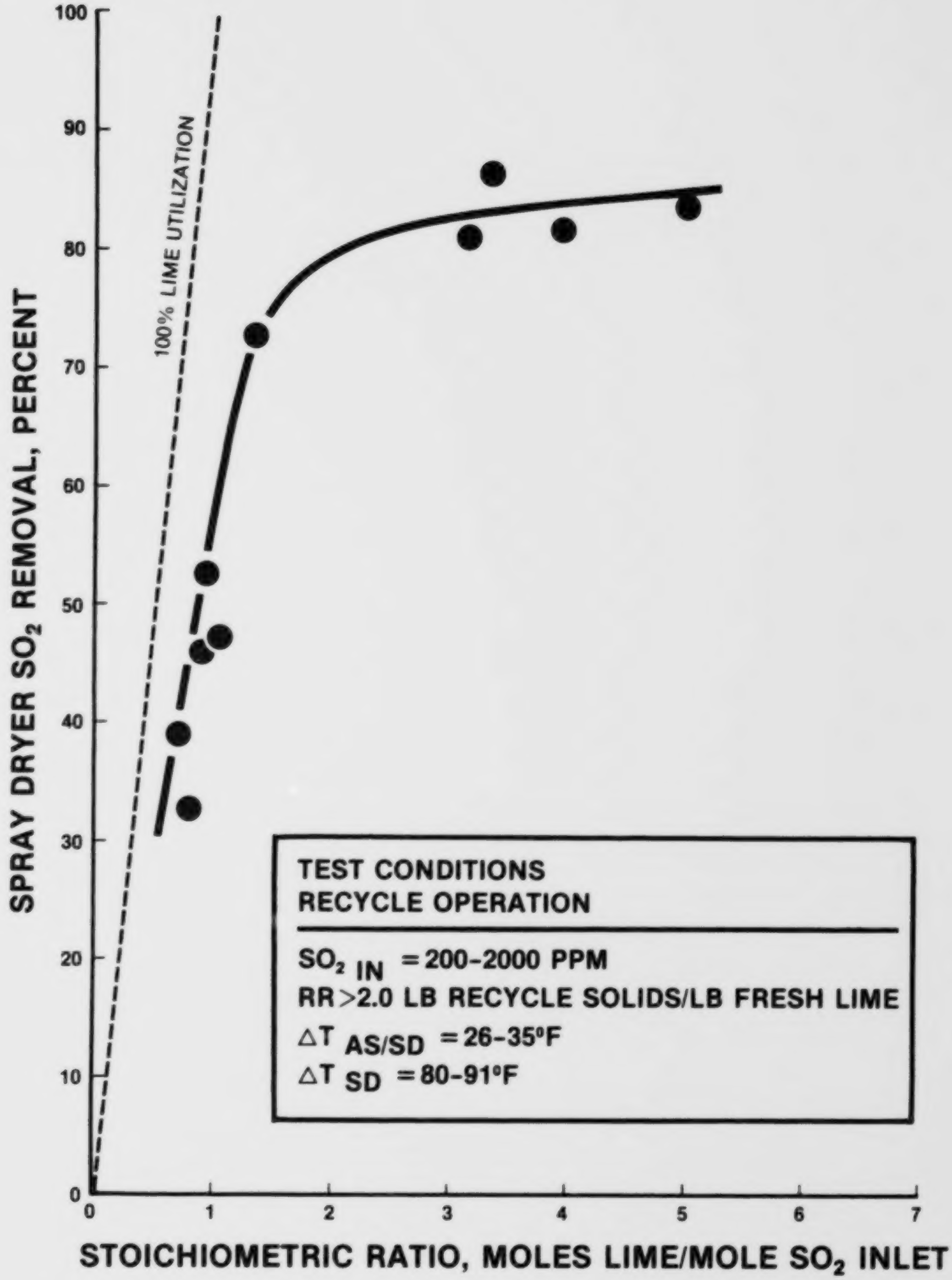


Figure 5-3. Effect of Stoichiometry on Spray Dryer SO_2 Removal at Low Spray Dryer Temperature Drop.

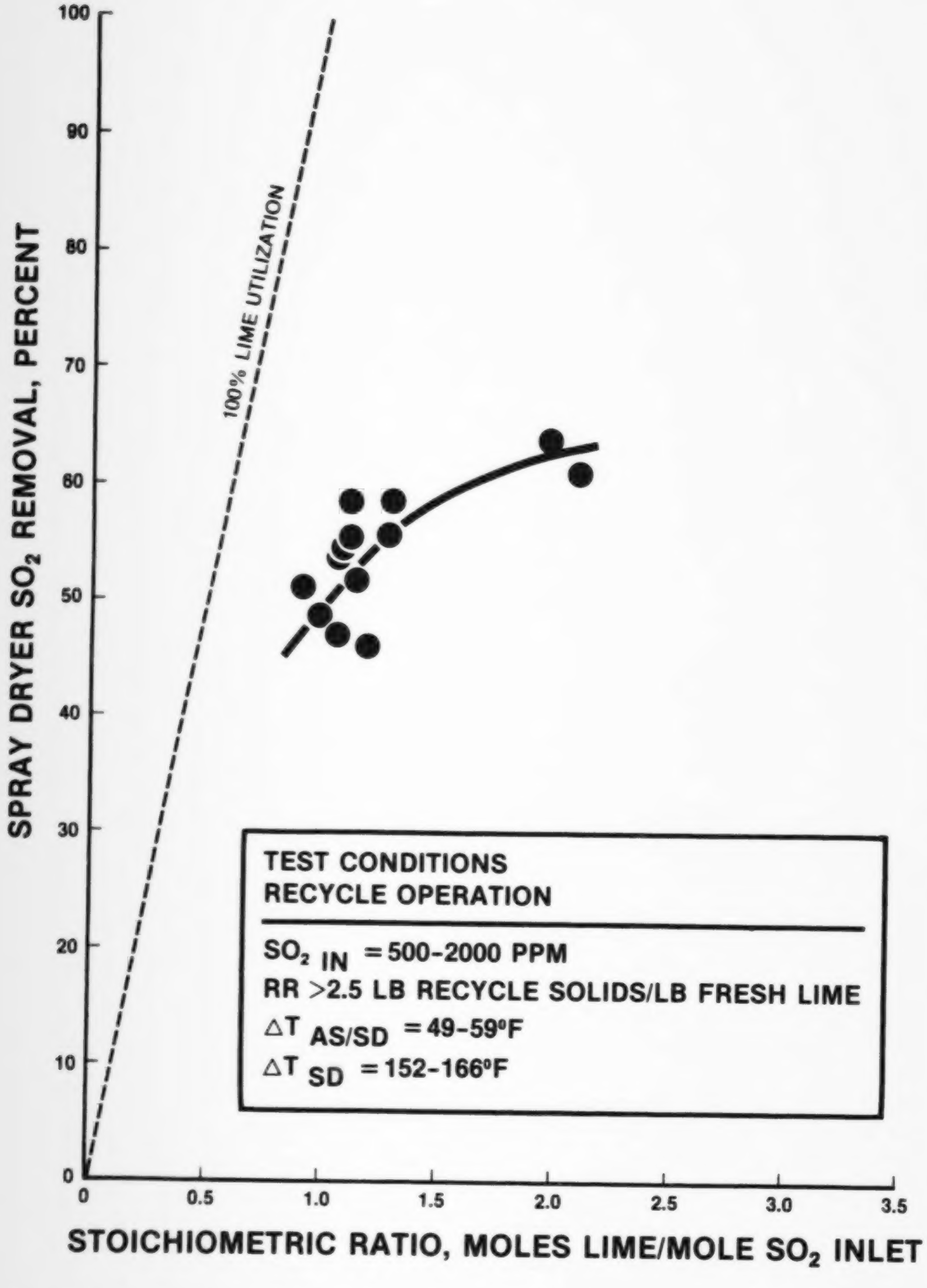


Figure 5-4. Effect of Stoichiometry on Spray Dryer SO_2 Removal at High Spray Dryer Temperature Drop and High Approach to Adiabatic Saturation Temperature.

ratio. As the value of stoichiometry approaches 1.0, the rate of increase SO_2 removal with stoichiometric ratio begins to drop off very sharply at the conditions tested. The plots of SO_2 removal vs. stoichiometry tend to remain near the 100 percent lime utilization line at low SR and then drop off dramatically at higher values of SR and percent SO_2 removal.

The point at which a sharp slope change occurs in Figures 5-2 through 5-4 is governed by the other system variables, especially those related to the degree of wetness of the slurry droplets. Flue gas temperature approach to adiabatic saturation ($\Delta T_{AS/SD}$) and temperature drop across the spray dryer (ΔT_{SD}) appear to be the important parameters. The amount of water initially present in the atomized slurry is proportional to ΔT_{SD}. Higher values of ΔT_{SD} produce more favorable conditions for SO_2 removal because of the increased water in the slurry droplets. At the same time, the rate of water evaporation from the slurry droplets is proportional to ΔT_{AS}. Lower values of ΔT_{AS} result in enhanced SO_2 removal because water is lost more slowly from the droplets.

Under the recycle conditions of Figures 5-2 through 5-4, SO_2 removal is improved over that in the lime-only runs, and the breakpoints in the curves occur at higher values of SO_2 removal. For example, in Figure 5-2 where $\Delta T_{AS/SD}$ = 26 to 35°F, SO_2 removal increases strongly with stoichiometry, breaks off sharply, and then increases more modestly in the 80 to 90 percent range. In Figure 5-4, where $\Delta T_{AS/SD}$ = 49 to 59°F, the curve breaks more gradually and at a value of SO_2 removal of only 50 to 60 percent.

At low stoichiometries ($SR < 1$), SO_2 removal in the spray dryer is extremely sensitive to stoichiometric ratio. At higher stoichiometries ($SR > 1.5$), there is sufficient lime reagent available so that stoichiometric ratio has much less effect. Increasing stoichiometry at these high levels serves mainly to reduce lime utilization. In this stoichiometry range the temperature variables, $\Delta T_{AS/SD}$ and ΔT_{SD}, have a stronger influence on SO_2 removal.

Approach to Adiabatic Saturation

Approach to adiabatic saturation, $\Delta T_{AS/SD}$, is defined as the difference between the spray dryer outlet flue gas temperature and the adiabatic saturation temperature. In the pilot tests, the bulk flue gas temperature was found nearly constant throughout the spray dryer and virtually identical to the outlet temperature.

The nearness of approach of the flue gas to the adiabatic saturation temperature is a strong indication of the degree of moisture in the slurry droplets. The reaction between lime and SO_2 occurs in the slurry liquid phase and, therefore, is favored by the presence of moisture. When the spray dryer is operated closer to saturation conditions, reaction conditions are more favorable and SO_2 removal is enhanced.

Lime-Only

Pilot plant results using lime-only show that the closer the spray dryer outlet temperature is to the adiabatic saturation temperature, the higher the percent SO_2 removal efficiency attained in the spray dryer. As Figure 5-5 shows, SO_2 removal in spray dryer increases from about 45 percent to about 80

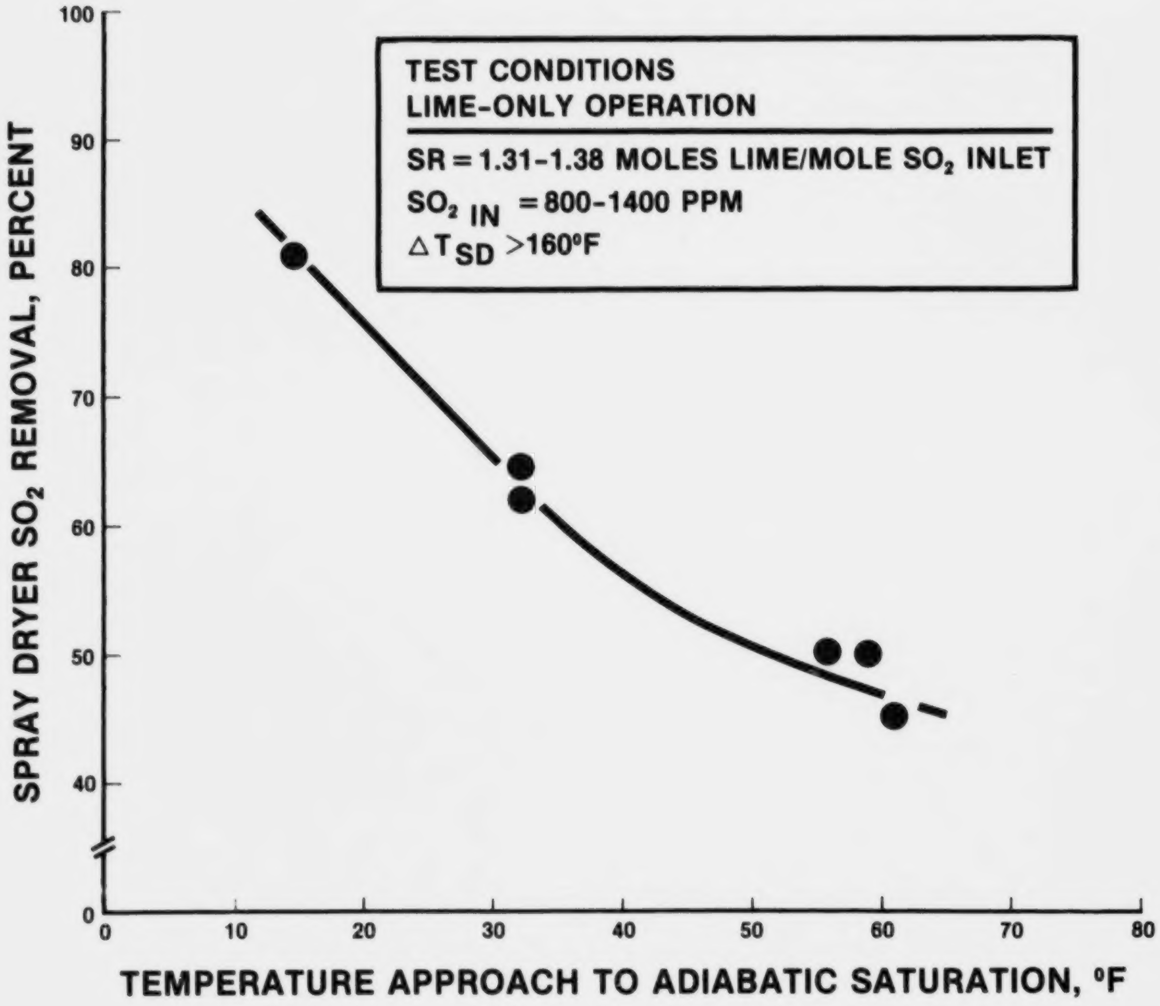


Figure 5-5. Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal - Lime-Only Operation.

percent as the approach to the adiabatic saturation temperature decreases from 60°F to about 20°F. Table 5.4 indicates that stoichiometric ratio and temperature drop across the spray dryer were held fairly constant for these runs.

TABLE 5.4 EFFECT OF ADIABATIC SATURATION TEMPERATURE ON SPRAY DRYER SO_2 REMOVAL

Run No.	Approach To Adiabatic Saturation (°F)	Stoichiometric Ratio (Moles Lime/ Mole SO_2 inlet)	Spray Dryer Temperature Difference (°F)	Spray Dryer SO_2 Removal (%)
111	34	1.62	141	62.4
118	15	1.31	200	81.0
119	32	1.37	182	64.4
120	61	1.35	160	44.8
203	69	1.31	160	49.8
501	56	1.38	158	50.2

The greatly improved SO_2 removal is apparently a result of the increased moisture retained by the slurry as it dries. Solids collected from the spray dryer bottoms show signficantly increased moisture content as the flue gas temperature approaches the adiabatic saturation temperature. Thus, the optimum operating temperature is the result of a balance between high SO_2 removal and trouble-free, continuous solids discharge from the spray dryer.

Recycle

SO_2 removal in the spray dryer increases sharply as the outlet temperature approaches the adiabatic saturation temperature, or as $\Delta T_{AS/SD}$ decreases, according to Figures 5-6 and 5-7. As shown in Figure 5-6, decreasing $\Delta T_{AS/SD}$ from 45°F to 25°F increases SO_2 removal in the spray dryer from 75 percent to 85 percent. At the higher stoichiometric ratios (>1.5), the approach to adiabatic saturation, which is set by the spray dryer outlet temperature, becomes the single most important factor affecting SO_2 removal across the spray dryer (Figure 5-7).

Solids collected from the spray dryer bottom show significantly increased moisture content as the flue gas temperature approaches adiabatic saturation (Figure 5-8). The increases in SO_2 removal and in spray dryer solids moisture content parallel each other fairly closely, according to a comparison of Figure 5-6 with Figure 5-8.

From the solids discharge standpoint, the spray dryer temperature observed for trouble-free operation using lime-only is about 5 to 10°F closer to the adiabatic saturation temperature than with recycle. Figure 5-8 shows this range of temperature difference between lime-only and recycle operation for an equivalent spray dryer solids moisture content.

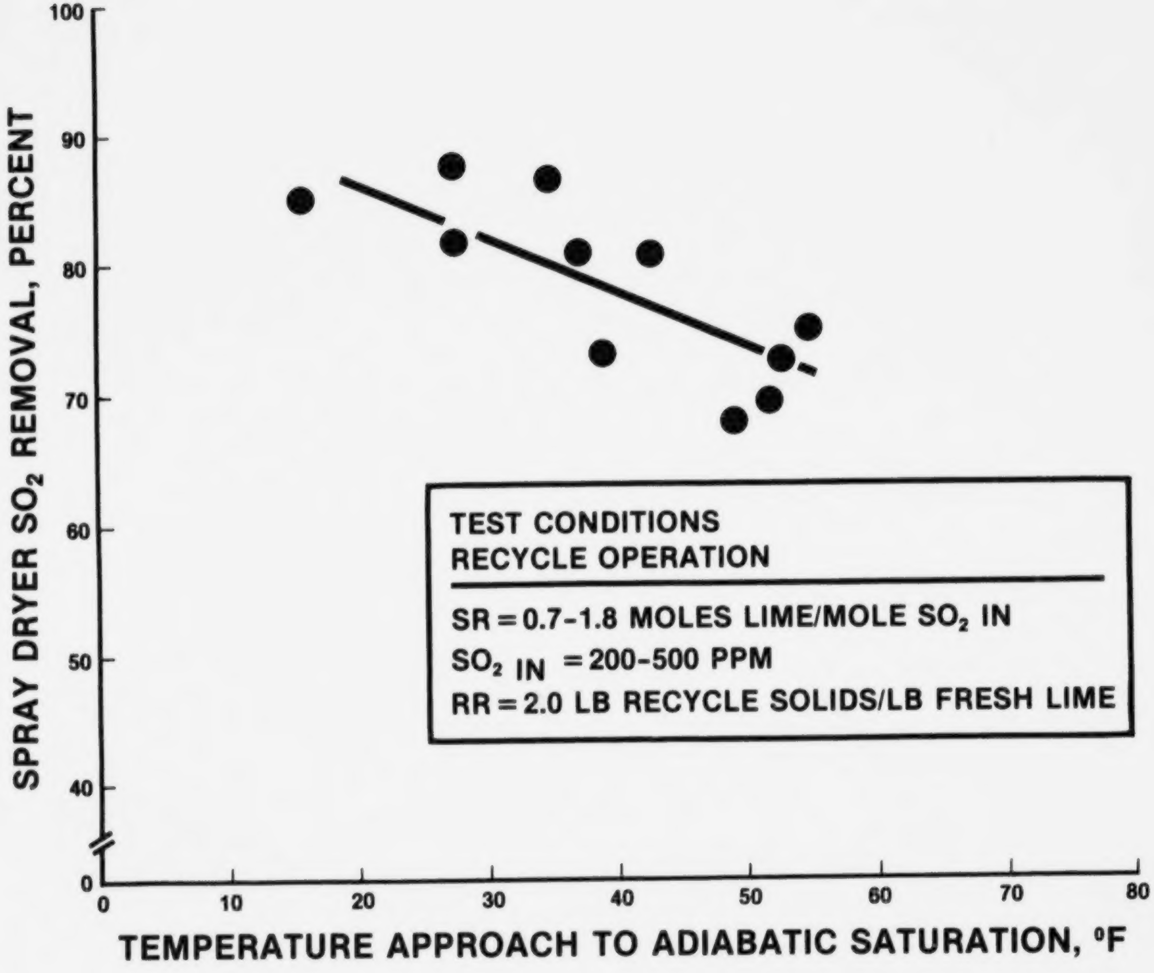


Figure 5-6. Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal - Recycle Operation.

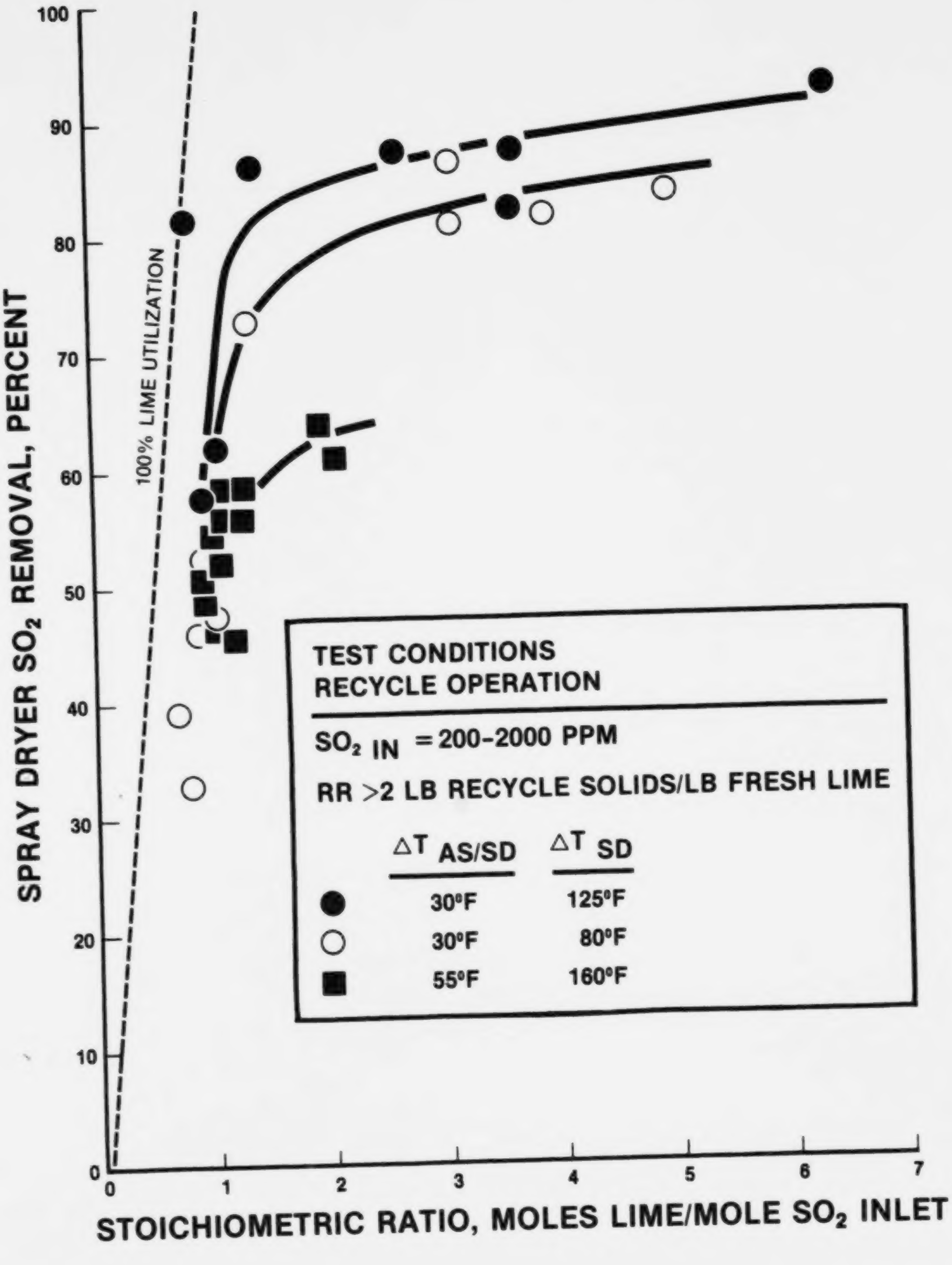


Figure 5-7. Effect of Temperature on Spray Dryer SO_2 Removal.

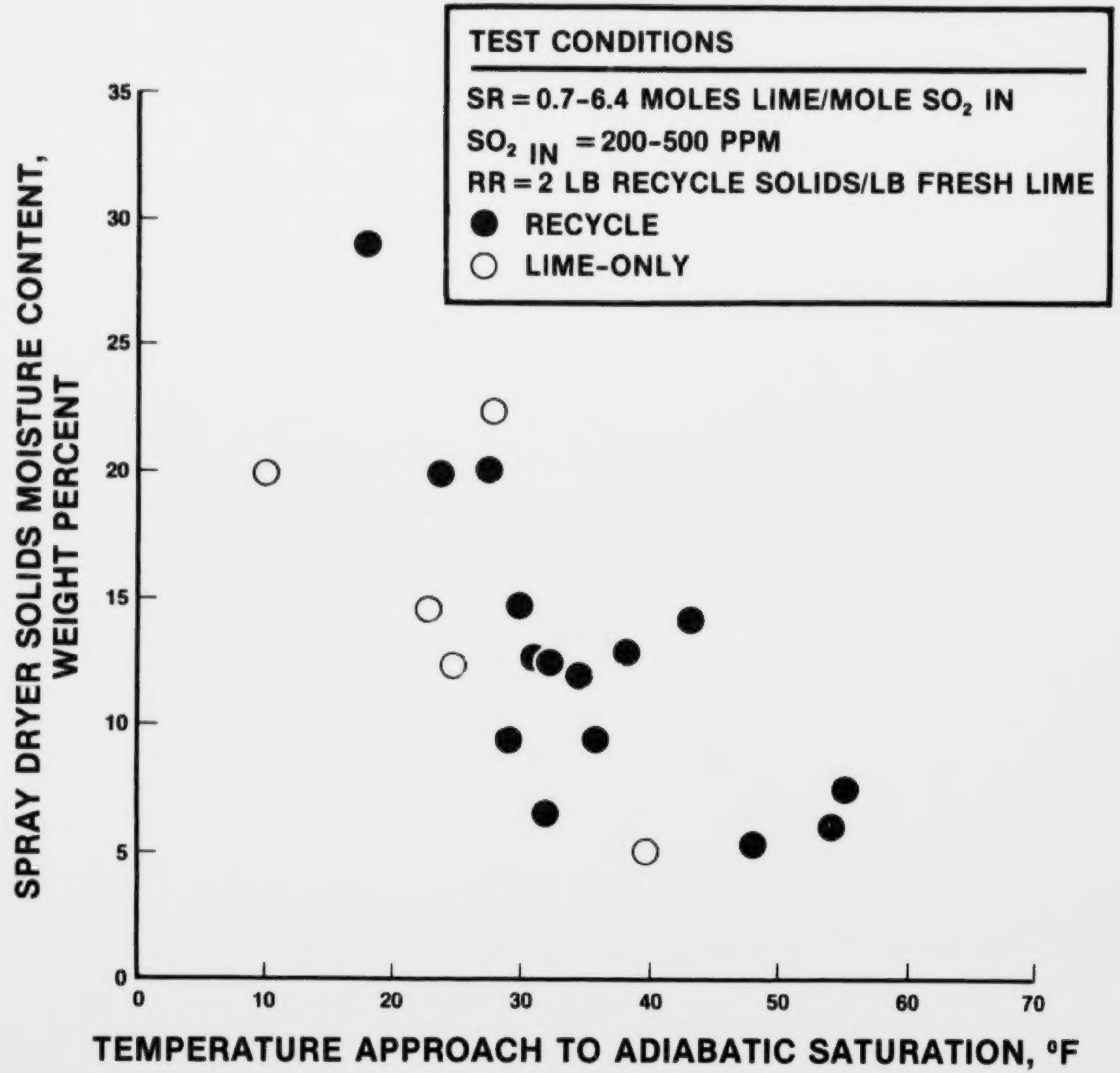


Figure 5-8. Effect of Adiabatic Saturation Temperature on Spray Dryer Solids Moisture Content.

Spray Dryer Temperature Difference

Spray dryer temperature difference, ΔT_{SD}, is defined as the difference between the spray dryer inlet and outlet flue gas temperature. The entering flue gas is cooled by the evaporation of water from the slurry droplets. From an energy balance, it can be seen that the flue gas temperature drop, ΔT_{SD}, is directly related to the liquid-to-gas ratio (L/G) fed to the dryer. As ΔT_{SD} is increased, more water is fed to the dryer per pound of flue gas and SO_2 removal across the spray dryer tends to increase as a result of the increased moisture in the reaction system. The increased moisture increases the time that a slurry droplet remains wet.

Lime-Only

Increasing the temperature drop across the spray dryer can be achieved either by increasing the inlet temperature or by decreasing the outlet temperature. The latter method of increasing ΔT_{SD} also lowers the approach to adiabatic saturation and improves SO_2 removal. Table 5.5 presents a number of runs conducted with varying inlet temperature while holding outlet temperature (approach to adiabatic saturation) and stoichiometric ratio relatively constant. Spray dryer SO_2 removal is plotted in Figure 5-9 as a function of temperature drop across the spray dryer for the runs listed in Table 5.5. Considerable improvement in SO_2 removal, from about 22 percent to about 40 percent, is achieved by increasing the temperature drop across the spray dryer, ΔT_{SD}, from 80°F to 160°F (Figure 5-9). Since more water must be added to the slurry to maintain a constant approach as ΔT_{SD} is increased, the added water improves the SO_2-lime reaction by keeping the droplet moist for a longer time.

TABLE 5.5 EFFECT OF TEMPERATURE DROP ACROSS THE SPRAY DRYER ON SPRAY DRYER SO_2 REMOVAL

Run No.	Spray Dryer Temperature Difference (°F)	Stoichiometric Ratio (Moles Lime/ Mole SO_2 inlet)	Approach To Adiabatic Saturation (°F)	Spray Dryer SO_2 Removal (%)
218	81	0.56	63	23.4
219	82	1.08	66	21.9
411	158	1.06	55	41.5
516	80	1.04	55	28.8
530	158	1.05	55	37.6
535	160	1.02	55	47.3
601	118	0.98	59	32.7
802	123	1.04	57	33.1
805	122	1.08	58	31.6
812	120	0.99	56	32.8
817	122	0.96	59	32.3
820	118	1.08	58	34.8

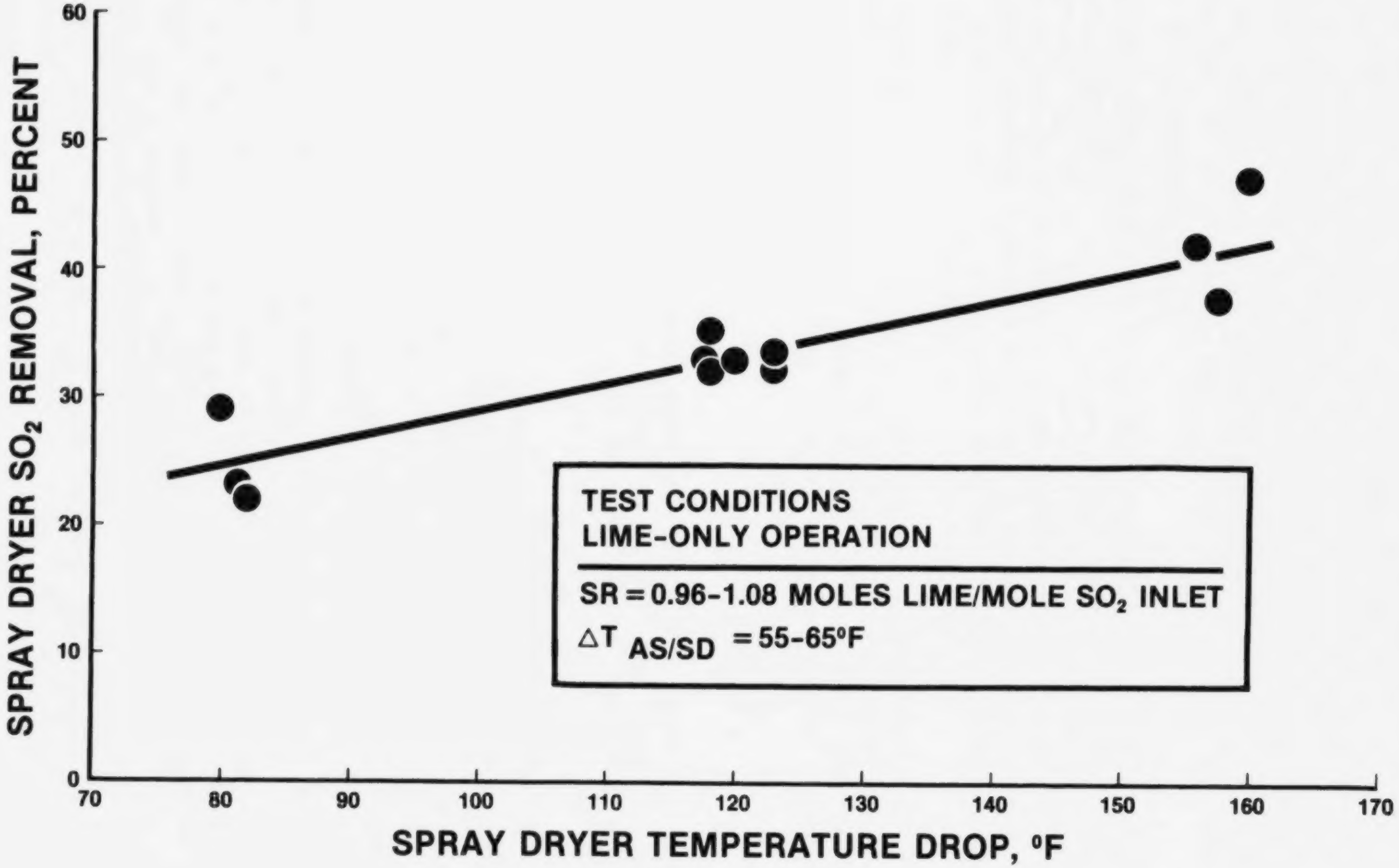


Figure 5-9. Effect of Spray Dryer Temperature Drop on Spray Dryer SO$_2$ Removal - Lime-Only Operation.

Recycle

Figures 5-10 through 5-12 show that increasing the flue gas temperature drop across the spray dryer increases SO_2 removal. For example, Figure 5-11 indicates that, on the flat part of the curve, SO_2 removal increases from about 82 percent to about 87 percent as ΔT_{SD} increases from 85 to 125°F. While the effect of approach to adiabatic saturation ($\Delta T_{AS/SD}$) on SO_2 removal is more pronounced than that of flue gas temperature drop (ΔT_{SD}), both process variables are significant. At higher stoichiometries (>1.5), manipulation of these temperature variables is the most effective way to improve SO_2 removal.

To best utilize the combined temperature effects on SO_2 removal in the spray dryer, the dryer outlet temperature should be maintained as low as practical. Maintaining the dryer outlet temperature as low as possible has the double benefit of a) decreasing $\Delta T_{AS/SD}$, and b) increasing ΔT_{SD} for a given flue gas inlet temperature.

The lowest feasible spray dryer outlet temperature is governed by product discharge constraints. As the flue gas temperature is decreased, SO_2 removal increases but the solids moisture content also increases to the point where difficulties arise in discharging solids from the spray dryer bottom. Thus, the optimum operating temperature strikes a balance between high SO_2 removal and trouble-free, continuous operation from the discharge and subsequent handling of high moisture content solids.

It may be desirable to reheat the flue gas prior to sending it to a baghouse in order to obviate the potential problems of condensation, corrosion, and bag blinding. This is a design problem with a variety of possible solutions, including partial bypass around the spray dryer and external (e.g., steam) reheating.

Recycle Ratio

Fairly high SO_2 removal percentages are attainable operating in a no-recycle (lime-only) mode at high stoichiometric values, but reagent utilization is low. Recycle of FGD solids product to the spray dryer is essential for an economically competititive process since it reduces the quantities of expensive lime reagent required.

Recycling of the product solids improves SO_2 removal in the spray dryer. The enhancement of SO_2 removal in the spray dryer is affected by the amount of material recycled (recycle ratio). Recycle ratio (RR) is defined as mass (or weight) of product solids recycled per unit mass (or weight) of fresh $Ca(OH)_2$ in the slurry fed to the spray dryer. The sources of the recycle solids are the spray dryer bottoms and/or the baghouse bottoms.

Figure 5-13 shows the beneficial effect of recycle ratio on SO_2 removal in the spray dryer. As the amount of recycled material (i.e., recycle ratio) increases, SO_2 removal increases. At values above RR = 2.5, SO_2 removal appears to level off, suggesting no benefit to recycling additional solids. For practical purposes, higher recycle ratios are beyond the range of interest because of slurry pumping limitations. In Figure 5-13, SO_2 removal increases from about 38 percent with lime-only (RR = 0) to about 49 percent at a recycle

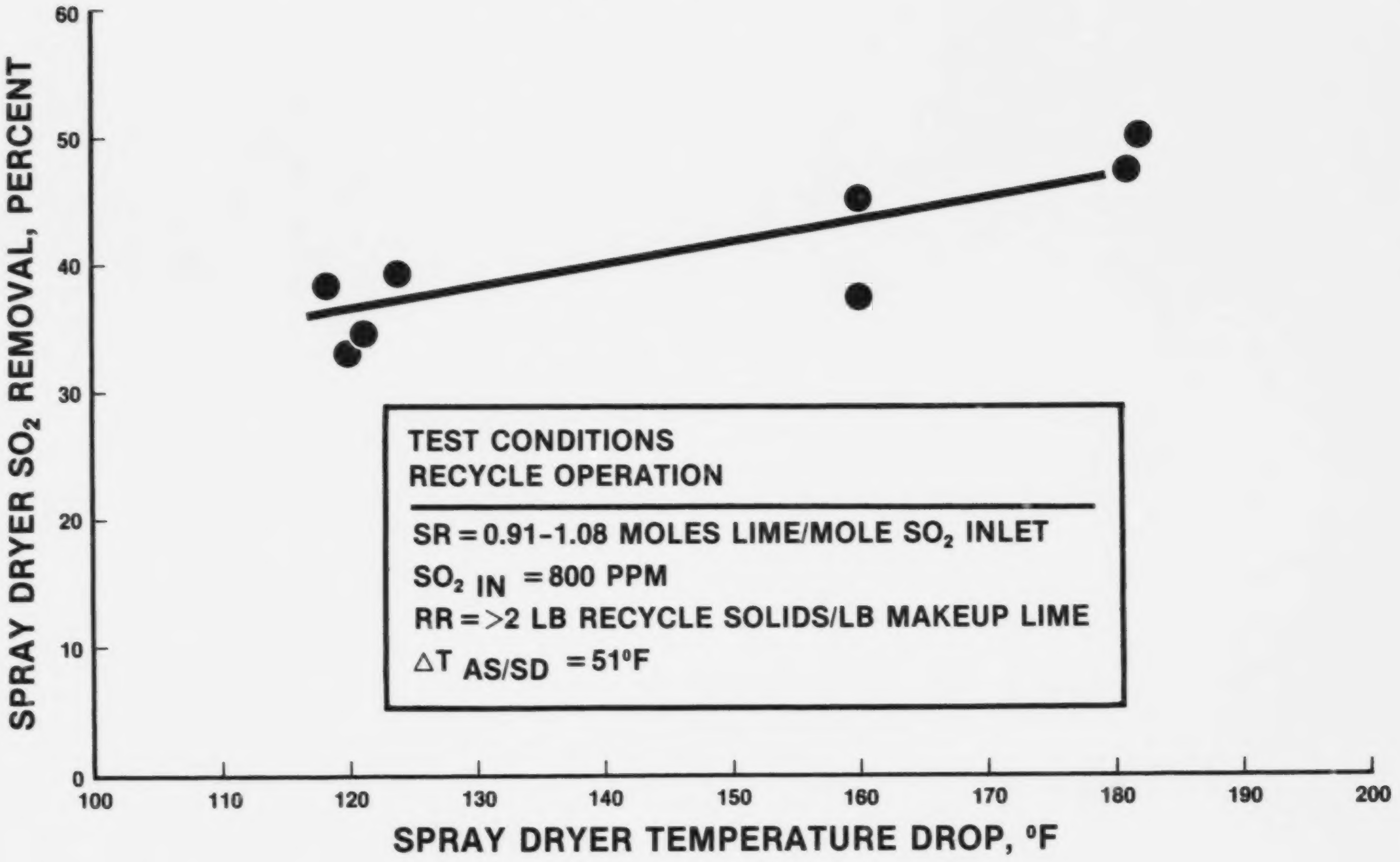


Figure 5-10. Effect of Spray Dryer Temperature Drop on Spray Dryer SO_2 Removal - Recycle Operation.

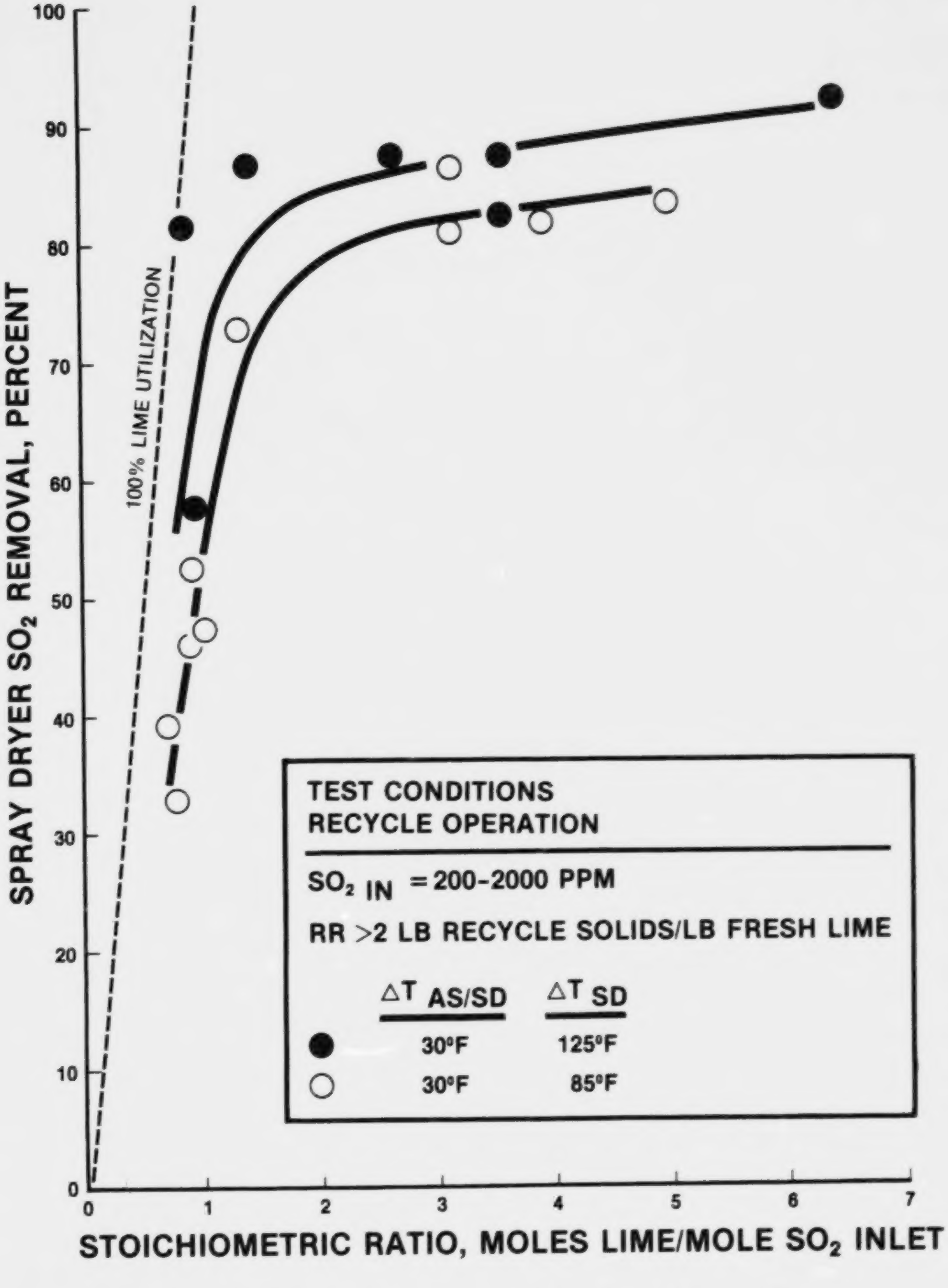


Figure 5-11. Comparison of Two Levels of Spray Dryer Temperature Drop for Spray Dryer SO_2 Removal.

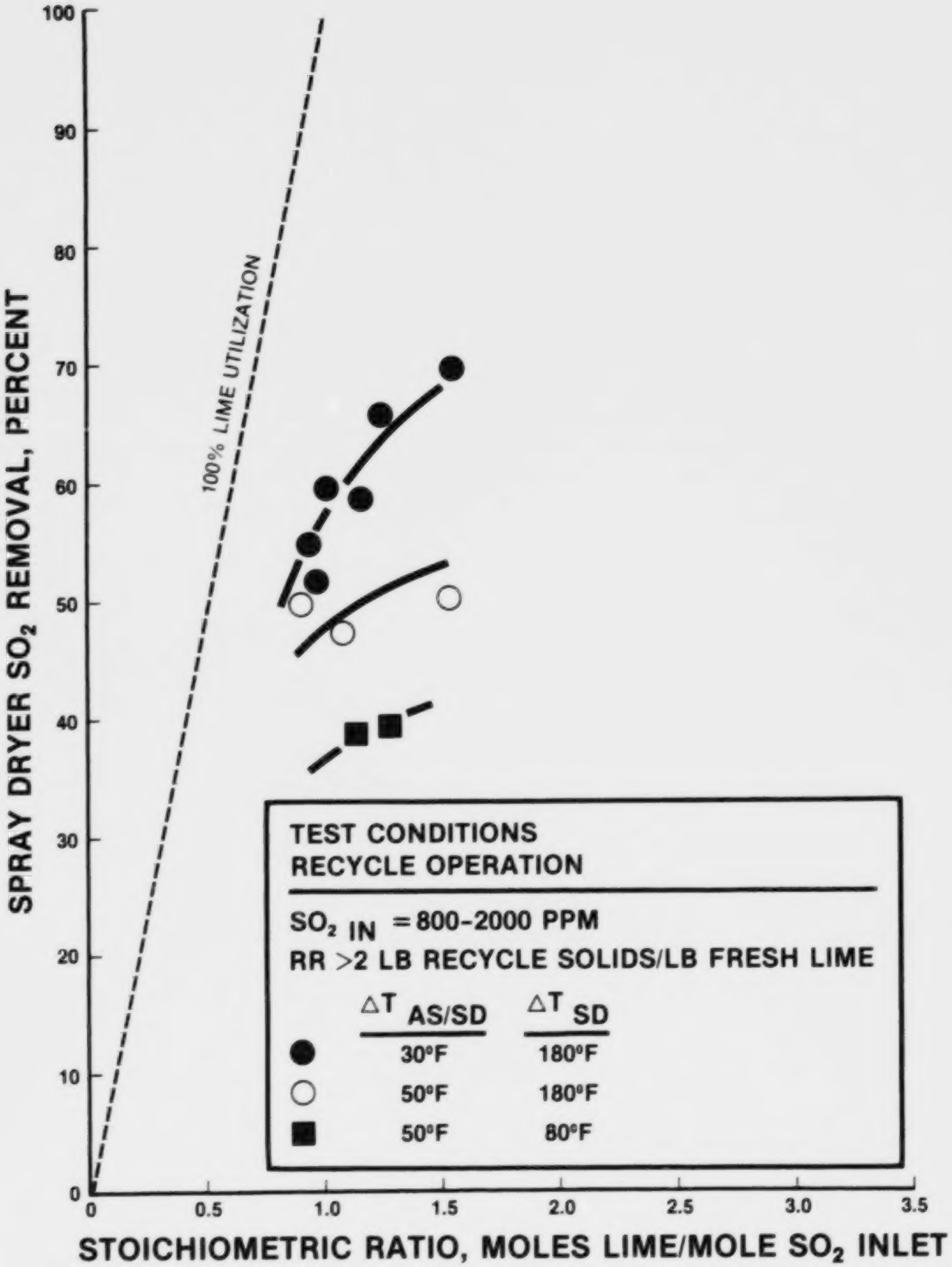


Figure 5-12. Effect of Spray Dryer Temperature Drop on Spray Dryer SO_2 Removal at Three Levels of Temperature Conditions.

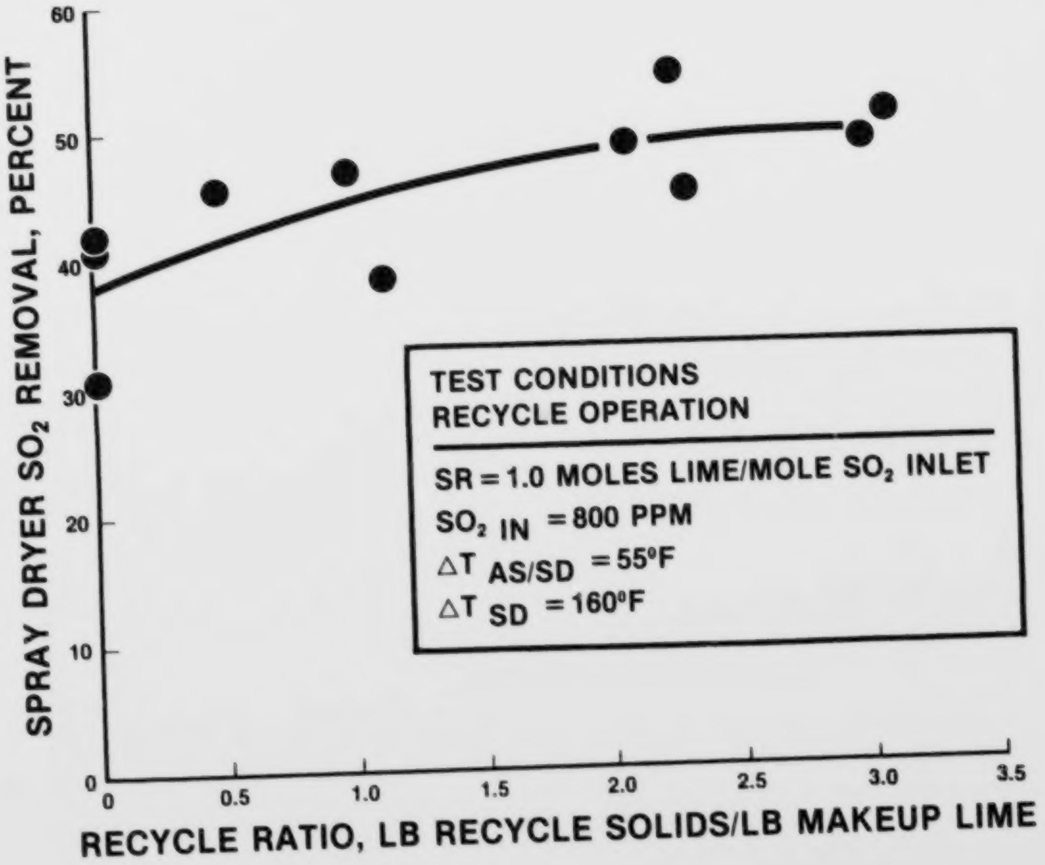


Figure 5-13. Effect of Recycle Ratio on Spray Dryer SO_2 Removal.

ratio of 2.5.

Two factors appear to contribute to improved SO_2 removal:

1. The recycle solids contain unreacted alkali. Collected solids are a mixture of flyash, unreacted lime, and FGD products. Both unreacted lime and flyash contain available alkali species.

2. The recycle solids act to increase the availability of the lime by providing surface area on which the slaked lime particles are dispersed. Thus, the area of lime contacting the flue gas is increased by spreading out the finer lime particles over the surface of the larger fly ash particles.

The increase in SO_2 removal observed with recycle is greater than can be accounted for based solely on the additional lime content of the recycle solids. Electron micrographs suggest that the lime present is made more available for reaction because of the increased area for dispersion on the recycle solids.

As the product solids recycle rate is increased, reagent utilization is improved, but the overall slurry feed solids concentration to the spray dryer is also increased because water usage is fixed. A limitation is reached at some point where pumping or atomization of the concentrated slurry is no longer efficient or possible. Difficulty in pumping a concentrated slurry by the spray dryer metering pump set the maximum recycle rate in the test program.

Although recycle ratio enhances SO_2 removal in the spray dryer, it is not as influential as the three predominant parameters: stoichiometry, flue gas temperature approach to adiabatic saturation and temperature drop in the spray dryer. While SO_2 removal using recycle is greater than with once-through lime operation, the general effects and trends of the dry scrubbing process parameters are similar.

Flue Gas Residence Time

Sufficient flue gas residence time in the spray dryer is essential in dry SO_2 scrubbing to permit SO_2 absorption from the gas phase and water evaporation in the drying of the FGD solids. SO_2 absorption and water evaporation rates are very high in first few seconds of gas-liquid contact when much of the SO_2 is absorbed and moisture evaporated. After the initial high rate period, the rates of SO_2 absorption and H_2O evaporation fall off rapidly and increased time is required for SO_2 removal and solids moisture reduction to reach the desired levels.

Lime-Only

As shown in Figure 5-14, spray dryer SO_2 removal increases slightly with increasing spray dryer residence time, θ_{SD}. From a point of 45% SO_2 removal at 8 seconds residence time, an increase of slightly less than one percent extra SO_2 removal was observed for each additional second of flue gas residence time in the spray dryer. The runs were carried out at nearly constant stoichiometric ratio, approach to adiabatic saturation temperature, and tem-

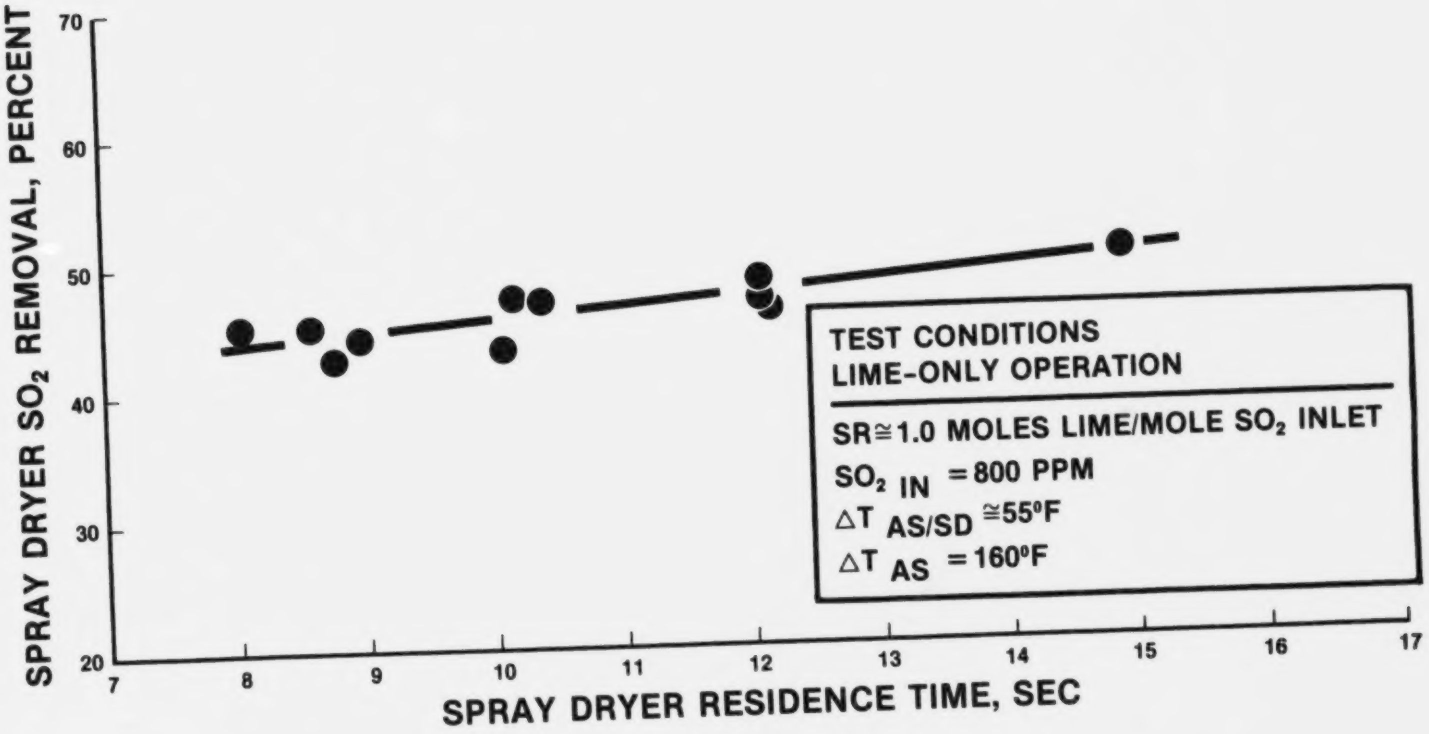


Figure 5-14. Effect of Residence Time on Spray Dryer SO_2 Removal - Lime-Only Operation.

perature difference in spray dryer (Table 5.6).

TABLE 5.6 EFFECT OF SPRAY DRYER RESIDENCE TIME ON SPRAY DRYER SO_2 REMOVAL

Run No.	Spray Dryer Residence Time (Seconds)	Stoichiometric Ratio (Moles Lime/ Mole SO_2 inlet)	Approach To Adiabatic Saturation (°F)	Spray Dryer Temperature Difference (°F)	Spray Dryer SO_2 Removal (%)
501R	10.4	1.04	50	161	46.8
502	8.1	1.19	58	159	45.0
503	9.0	1.25	60	160	44.0
503R	8.8	1.14	59	162	42.4
504	12.2	0.96	52	160	45.7
504R	12.1	1.00	45	161	46.5
505	14.9	1.07	35	149	50.0
534	8.6	1.13	47	161	45.2
535	10.2	1.02	55	160	47.3
536	12.1	1.04	49	160	48.0
538	10.1	1.04	52	159	43.1

Recycle

Flue gas residence time in the spray dryer appears to have no significant effect on SO_2 removal when operating under recycle conditions over the range from 8 to 16 seconds. Figure 5-15 shows that no trend is discernible for the limited number of runs conducted. It is likely that gas residence time becomes important only at lower residence times where water evaporation and SO_2 removal are rapid. Residence time was varied by changing the inlet flue gas flow rate to the dryer.

Flue Gas Inlet SO_2 Concentration

In practice, the SO_2 concentration in the incoming flue gas is determined by coal sulfur content and boiler operating conditions (excess air). This study investigated a wide range of inlet SO_2 concentrations (185 to 2150 ppmv). Most of process variable tests were conducted at a flue gas inlet SO_2 concentration of about 800 ppm. The 800 ppm SO_2 level was thought to be meaningful since it represents the upper end of the concentration range of the low sulfur coals used in the utility dry scrubbing systems awarded prior to the test program. Series of tests were also conducted at lower (200 to 500 ppm) and higher (1400 and 2000 ppm) inlet SO_2 concentrations. The normal Comanche station flue gas SO_2 concentration ranged from about 200 to 400 ppm during the test program. Inlet concentrations to the spray dryer in excess of the normal plant level were achieved by spiking the flue gas with SO_2 from cylinders via a pressurized delivery system.

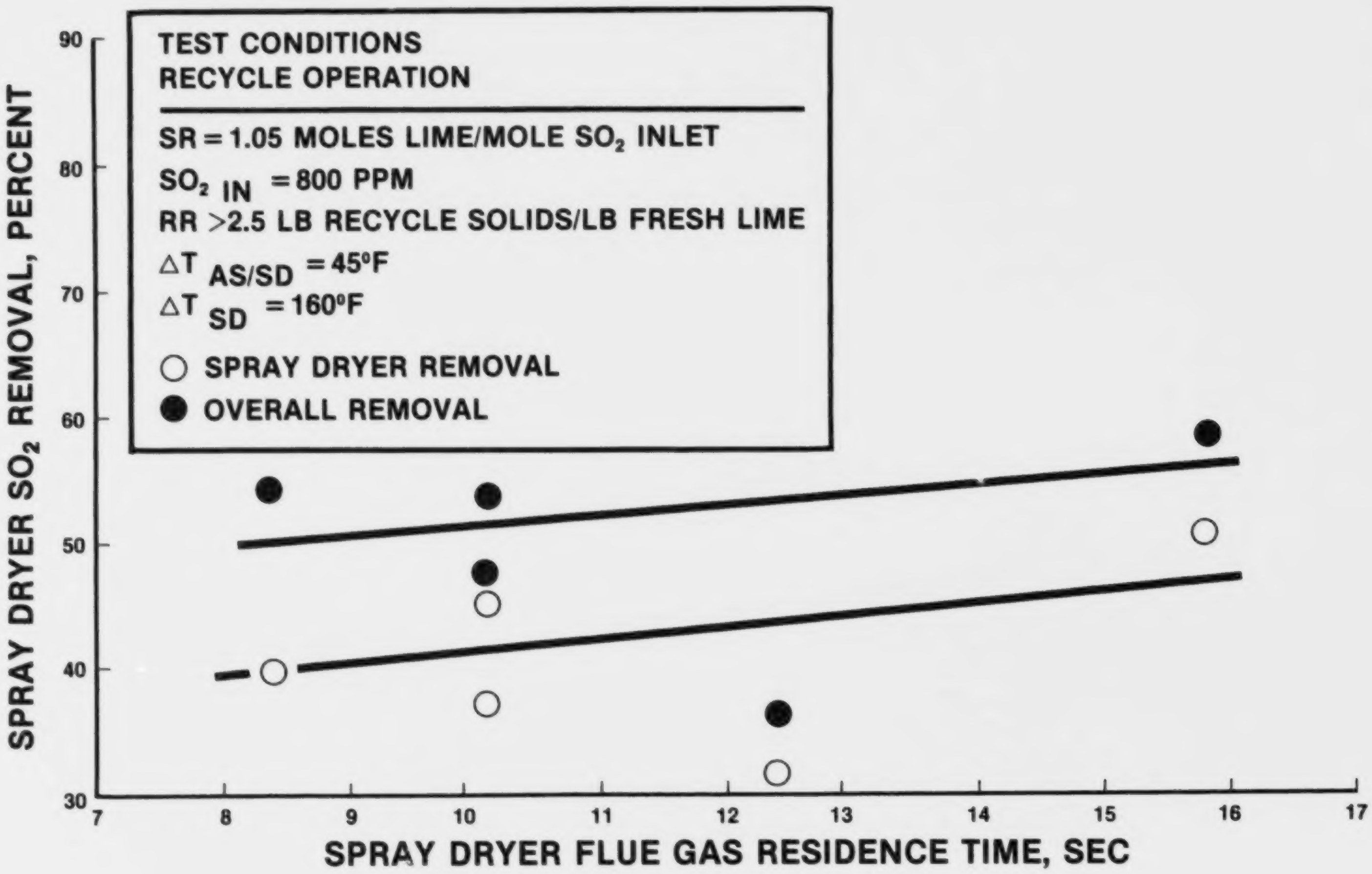


Figure 5-15. Effect of Residence Time on Spray Dryer SO_2 Removal - Recycle Operation.

Lime-Only

Figure 5-16 indicates that the SO_2 removal in the spray dryer is affected little by the inlet flue gas SO_2 concentration. A very slight drop in the SO_2 removal may occur as the SO_2 is increased, but the trend is weak. In the statistical treatment of a larger number of runs than shown in Figure 5-16 and conducted with lime-only, no significant effect of inlet SO_2 concentration in SO_2 removal was calculated. Table 5.7 presents the pertinent process conditions for the runs plotted in Figure 5-16.

TABLE 5.7 EFFECT OF SPRAY DRYER INLET SO_2 CONCENTRATION ON SPRAY DRYER SO_2 REMOVAL

Run No.	Inlet SO_2 Concentration (ppm)	Stoichiometric Ratio (Moles Lime/ Mole SO_2 inlet)	Approach To Adiabatic Saturation (°F)	Spray Dryer SO_2 Removal (%)
109	800	1.28	62	40.6
207R	1365	1.08	68	39.0
308R	2000	0.91	68	32.4
607	790	1.05	53	35.6
619	810	1.03	55	34.0
213	1320	1.03	47	46.0
311	2075	1.10	46	48.3
505	740	1.07	40	51.0

Recycle

Inlet SO_2 concentration has no significant effect on SO_2 removal in the spray dryer under recycle conditions, according to Figure 5-17. Any small influence of inlet SO_2 concentration is insignificant compared to that of stoichiometry and/or temperature. A small variation in any of the predominant independent variables (SR, $\Delta T_{AS/SD}$, ΔT_{SD}) readily masks the effect of SO_2 concentration.

However, the amount of lime reagent needed for SO_2 removal is directly related to the SO_2 concentration in the inlet flue gas to the spray dryer. As inlet SO_2 concentration is increased, a greater amount of lime is required to achieve a given stoichiometric ratio. In addition, as SO_2 concentration is increased, the SO_2 removal required by the NSPS also increases which results in a greater stoichiometry requirement. Since the maximum quantity of water fed to the dryer per cubic foot of flue gas is fixed by the allowable flue gas temperature drop across the dryer, the lime slurry concentration increases as the inlet SO_2 concentration increases.

The pilot tests show that the maximum combined lime and recycle solids slurry concentration that can be pumped reliably is 35 wt. percent total solids. At a recycle ratio of 2.5 lb solids per lb fresh $Ca(OH)_2$, the equivalent lime slurry concentration is 10 wt. percent $Ca(OH)_2$; at 0.5 lb/lb, the

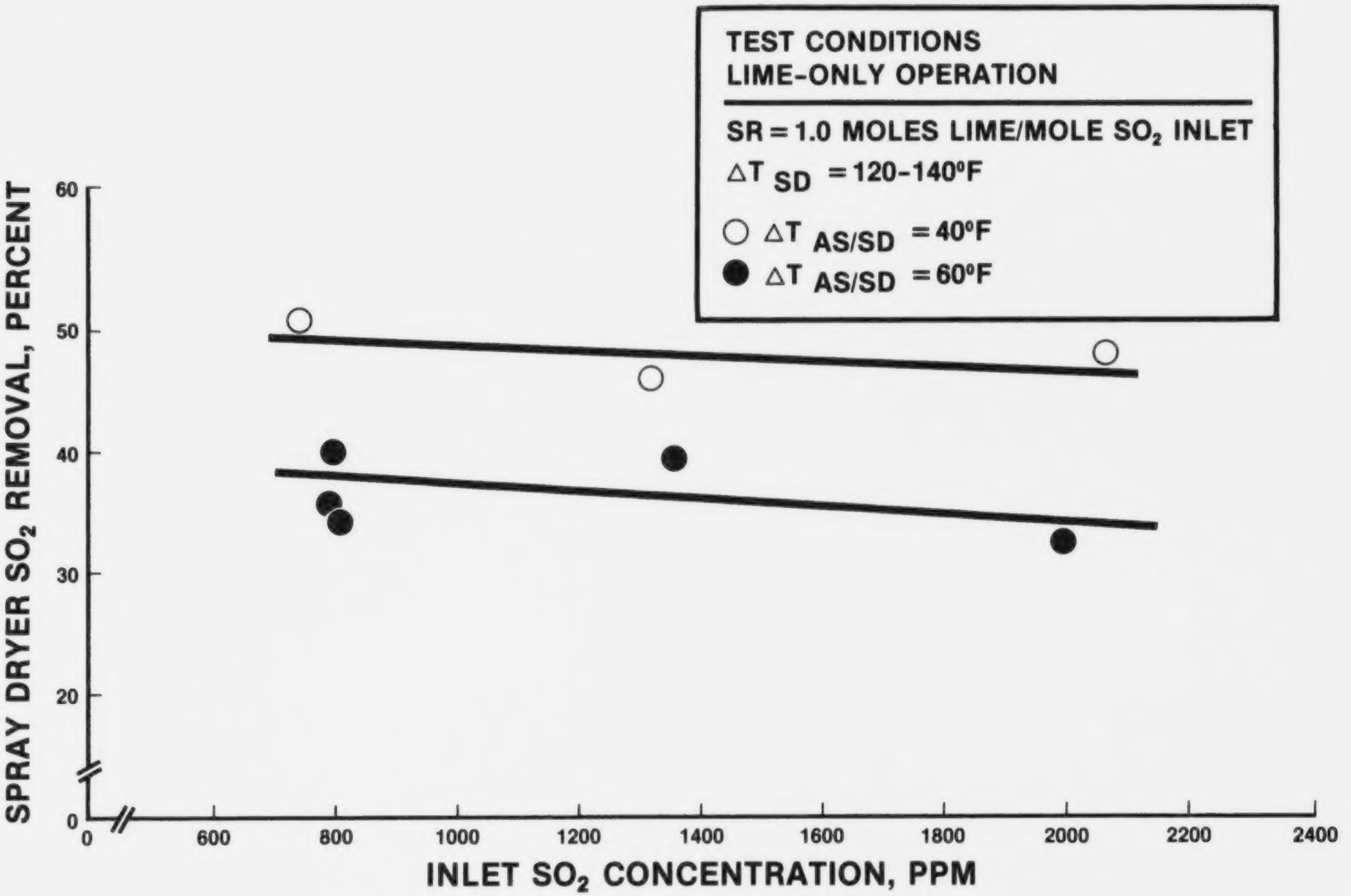


Figure 5-16. Effect of Inlet SO_2 Concentration on Spray Dryer SO_2 Removal - Lime-Only Operation.

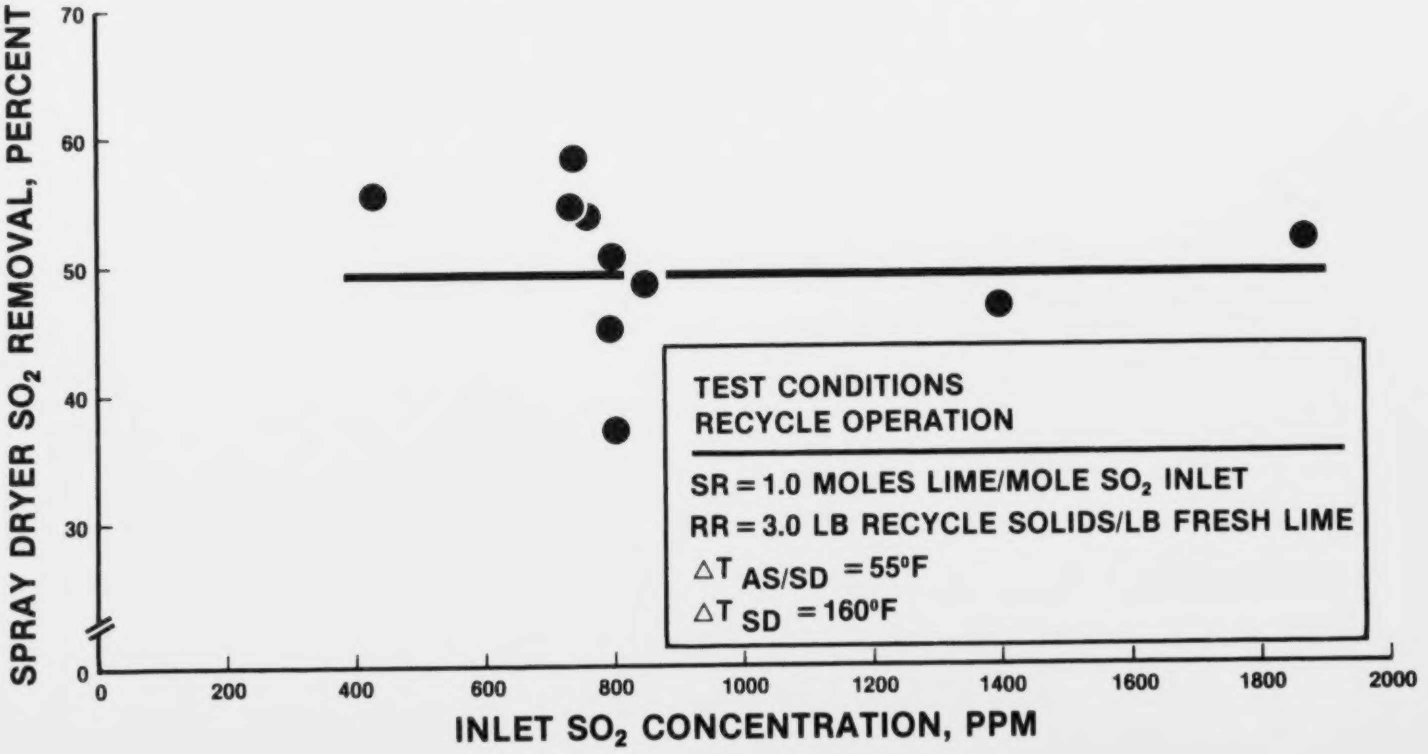


Figure 5-17. Effect of Inlet SO_2 Concentration on Spray Dryer SO_2 Removal - Recycle Operation.

equivalent lime slurry concentration equals 23.3 wt. percent. Hence, the ability to treat flue gases with a higher SO_2 content is limited not by chemical process considerations but rather by materials handling constraints (slurry pumping capability).

Spray Dryer SO_2 Removal Correlations

During the present dry scrubbing pilot study, the effects of many variables on SO_2 removal were investigated. Some of the variables were found to have no effect on spray dryer SO_2 removal. For other variables, the effect was limited to a small number of tests that did not show statistical significance when tested in any of the general correlations.

Lime-Only

The following parameters were consistently found to dominate spray dryer performance with regard to SO_2 removal. They are listed in order of decreasing impact on SO_2 removal efficiency:

- Stoichiometric Ratio (SR)
- Approach to Adiabatic Saturation Temperature ($\Delta T_{AS/SD}$)
- Temperature Drop Across the Spray Dryer (ΔT_{SD})

A mathematical equation correlating spray dryer SO_2 removal to SR, $\Delta T_{AS/SD}$, and ΔT_{SD} was developed from a total of 103 lime-only runs. The ranges of these parameters covered in the test runs analyzed are:

Variable	Range
Stoichiometric Ratio	0.56-5.9 moles lime/mole SO_2 in
$\Delta T_{AS/SD}$	15-80°F
ΔT_{SD}	80-200°F

A considerable number of theoretical and empirical mathematical relationships were tested to arrive at a spray dryer correlation. The equations were evaluated via a computer-aided multiple regression analysis (MUL-REGRESSION Routine of the STATSYSTEM** Program). The complexity of the relationships tested is limited by the fact that the multiple regression analysis handles only linear equations. Therefore, any relationship must be linear or able to be transformed into a linear equation before an analysis can be carried out.

Of the relationships tested, the equation that results in the correlation with the highest multiple correlation coefficient (r=0.96) and the smallest standard error of estimate (se=4.65) is:

$$\text{Spray Dryer } SO_2 \text{ Removal, \%} = -14.1 + 14.26(SR) - 1.32(SR)^2 + 12.8(T) - 0.53(T)^2 \quad (5\text{-}6)$$

where: SR = Stoichiometric Ratio (moles lime/mole SO_2 inlet)

T = Dimensionless Temperature Difference

$= (T_{IN/SD} - T_{AS/SD})/(T_{OUT/SD} - T_{AS/SD})$

$= (\Delta T_{SD} + \Delta T_{AS/SD})/(\Delta T_{AS/SD})$

$$= 1 + (\Delta T_{SD}/\Delta T_{AS/SD})$$

The correlating parameters, ΔT_{SD} and $\Delta T_{AS/SD}$, are calculated directly from observed flue gas temperature measurements. They reflect gas phase temperature changes from all sources including water addition, heat of reaction, convective heat loss and air leakage into the spray dryer.

The spray dryer SO_2 removal correlation of Equation (5-6) predicts SO_2 removal in the spray dryer fairly accurately for the range of variables covered. Figure 5-18 compares spray dryer SO_2 removal actually achieved versus that predicted by Equation (5-6). As Figure 5-18 shows, good agreement is obtained between actual and predicted SO_2 removal in the spray dryer over the entire range. Spray dryer SO_2 removals versus stoichiometric ratio, at specific values of $\Delta T_{AS/SD}$ and ΔT_{SD}, are plotted in Figures 5-19 and 5-20 to illustrate the degree to which the mathematical equation represents the actual data.

Recycle

A list of the pertinent process variables for the 76 recycle runs is included in Appendix A. The predominant independent variables that affect SO_2 removal in the spray dryer are stoichiometric ratio (SR), approach to adiabatic saturation temperature ($\Delta T_{AS/SD}$), flue gas temperature drop (ΔT_{SD}), and solids recycle ratio (RR). This result agrees with conclusions reached by visual inspection of the data when they are displayed graphically.

SO_2 removal across the spray dryer was correlated to the dominant independent variables to develop a mathematical equation for recycle conditions. An empirical equation of the following form was fitted:

$$\text{Spray Dryer } SO_2 \text{ Removal, \%} = 14.75(SR)-0.16(SR)^2-2.17(RR)+0.86(RR)^2+9.27(T)-0.43(T)^2 \qquad (5\text{-}7)$$

where SR is the lime stoichiometric ratio, RR is the recycle ratio and T is related to the approach to adiabatic saturation ($\Delta T_{AS/SD}$) and to the temperature drop across the spray dryer (ΔT_{SD}) by

$$T = 1 + \frac{\Delta T_{SD}}{\Delta T_{AS/SD}} \qquad (5\text{-}8)$$

Equation (5-7) accounts for 98.3 percent of the variation in SO_2 removal across the spray dryer with a standard error of 6.48 percent (absolute). Figure 5-21 presents a parity plot of observed SO_2 removal versus predicted SO_2 removal by Equation (5-7.)

FABRIC FILTER SO_2 REMOVAL

The spray dryer is the primary SO_2 control unit in the dry scrubbing system, and the fabric filter is the primary particulate control element. However, a significant amount of SO_2 removal occurs across the fabric filter. In the range of conditions tested in the pilot plant, the fabric filter removes 15 to 20 percent of the total SO_2 removal in the system.

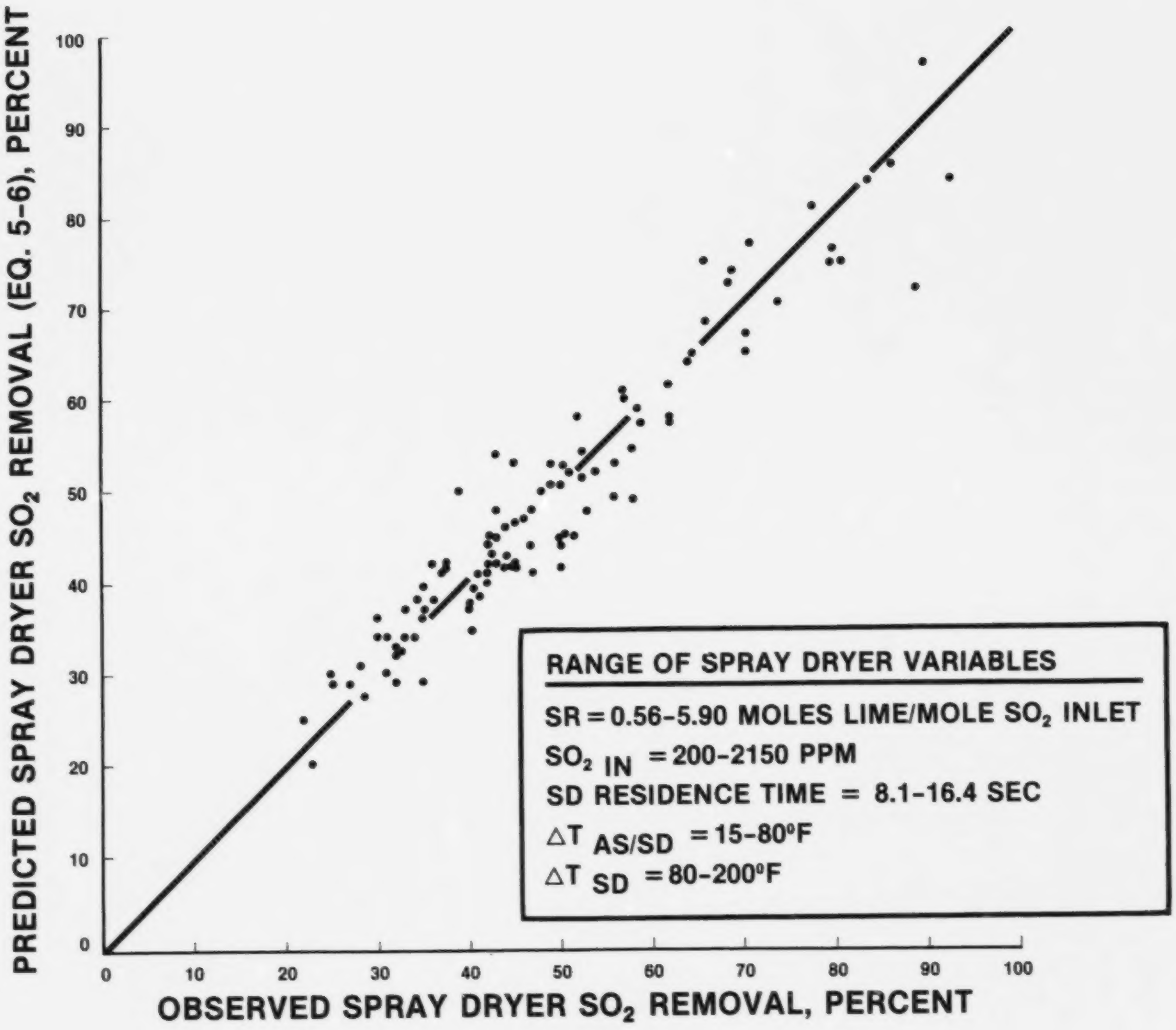


Figure 5-18. Parity Plot of Observed and Predicted Spray Dryer SO_2 Removal - Lime-Only Operation.

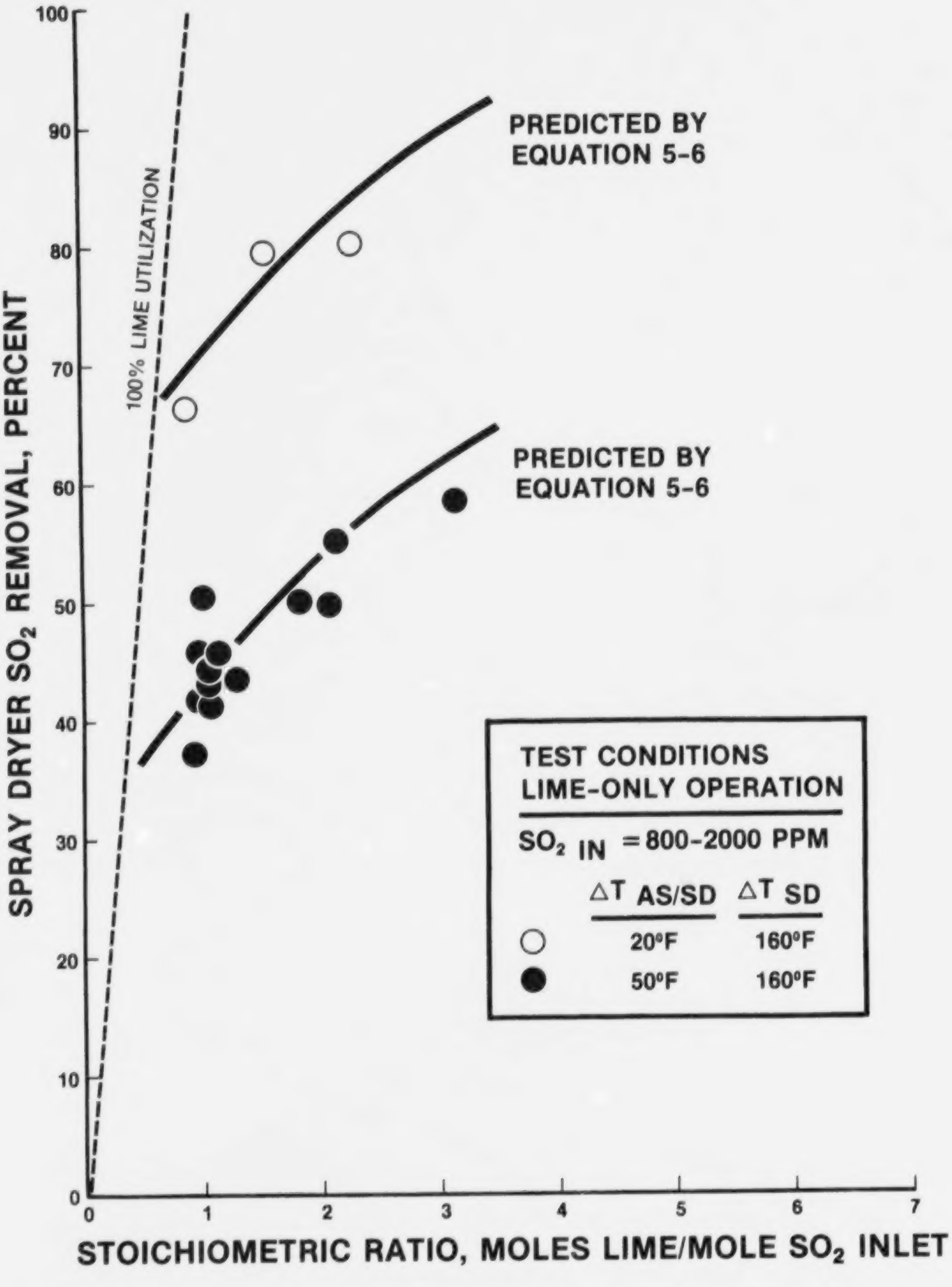


Figure 5-19. Comparison of Observed and Predicted Spray Dryer SO_2 Removal at High Spray Dryer Temperature Drop.

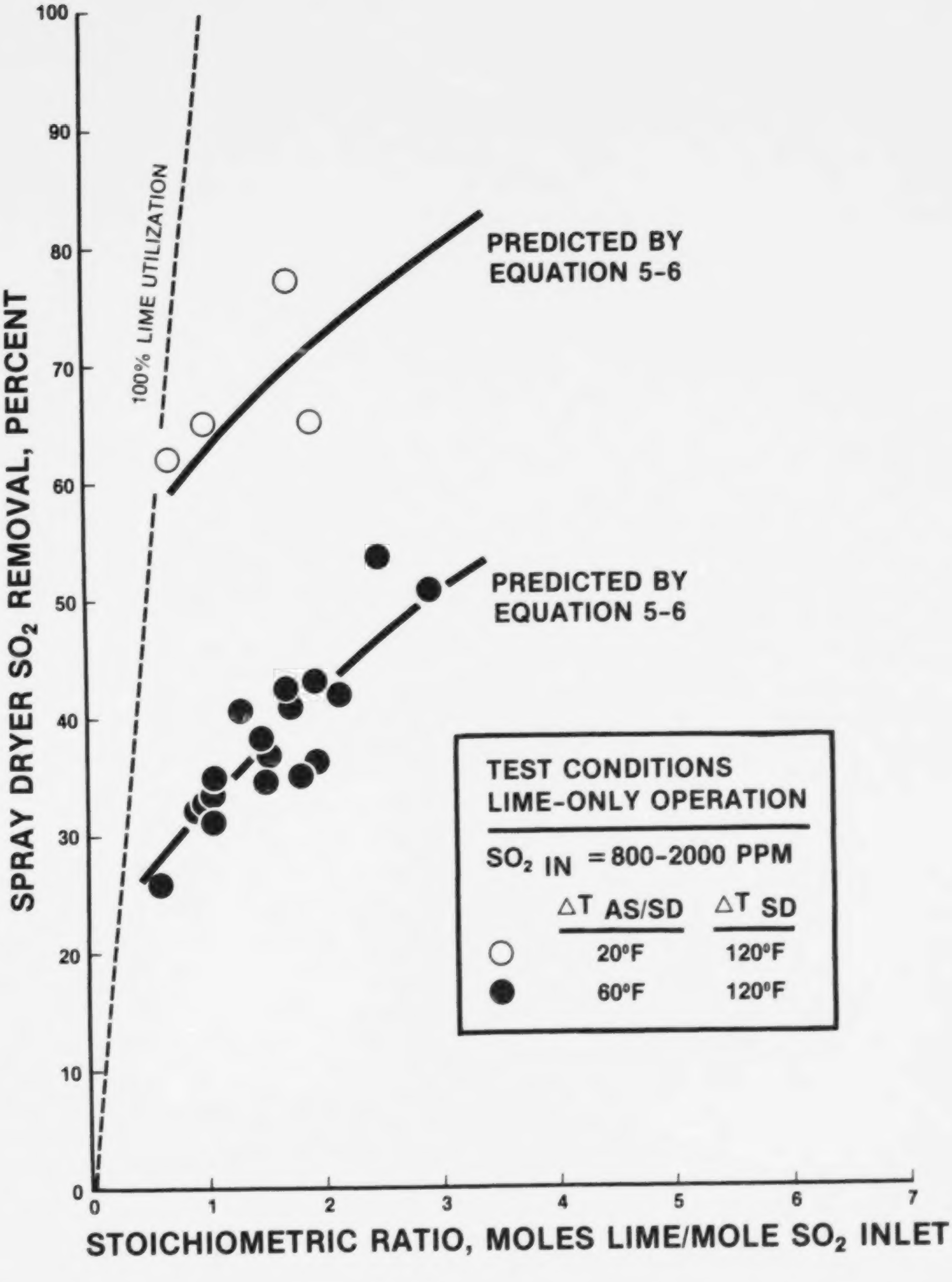


Figure 5-20. Comparison of Observed and Predicted Spray Dryer SO_2 Removal at Moderate Spray Dryer Temperature Drop.

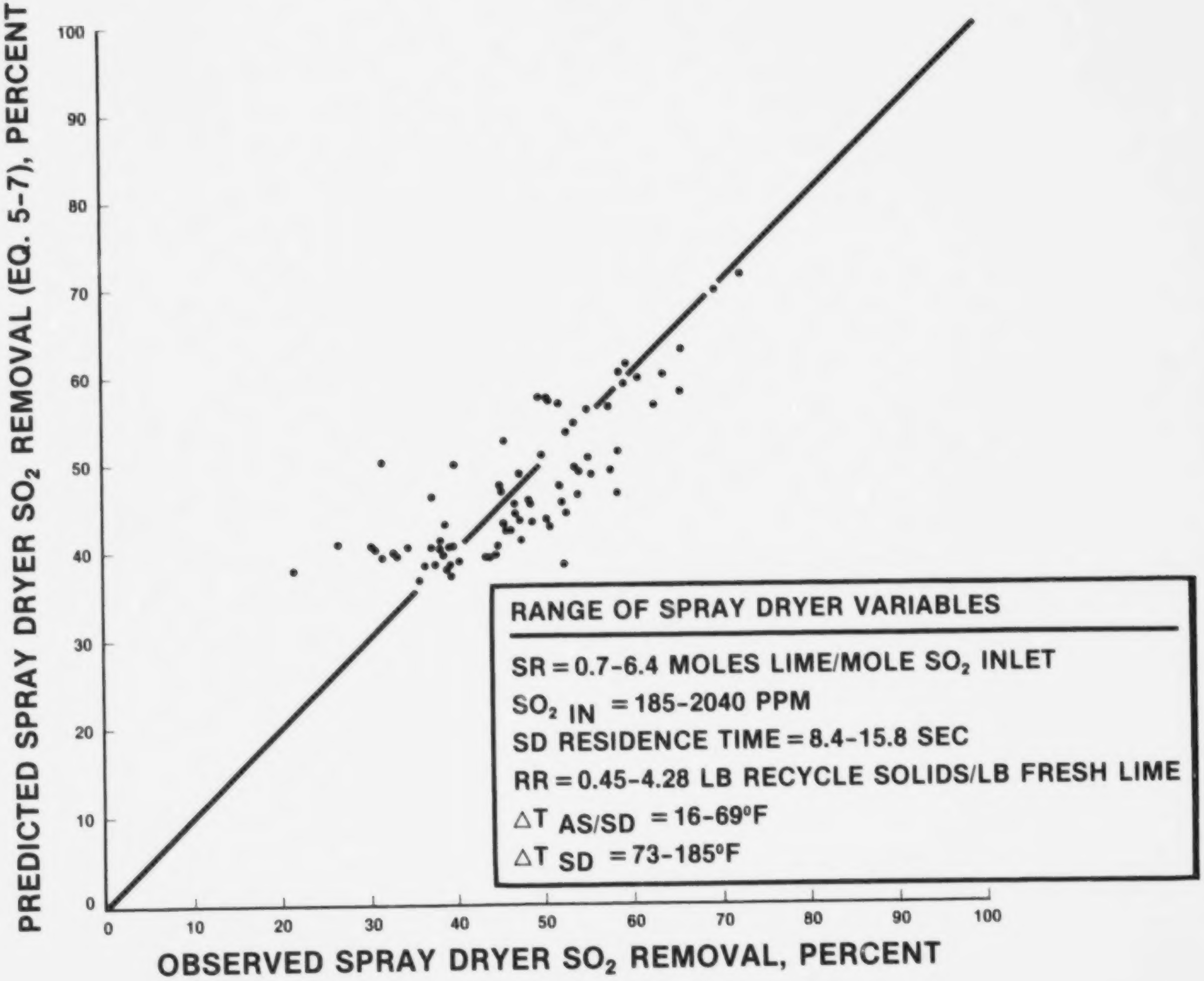


Figure 5-21. Parity Plot of Observed and Predicted Spray Dryer SO_2 Removal - Recycle Operation.

In the fabric filter, a thin layer of solid particles containing flyash, FGD products, and unreacted lime continually accumulates on the surface of the filter bags. Flue gas with a reduced SO_2 concentration from that entering the dry scrubbing system flows through the finely divided solids. Additional SO_2 removal occurs although the gas contact time in the bed is short.

Primary emphasis in the pilot test program was given to SO_2 removal performance in the spray dryer. For this reason, a study of the effect of the fabric filter operation on SO_2 removal was less extensive. The investigation of fabric filter effects took place simultaneously with the testing of the spray dryer. The fabric filter variables explored in the field test program were:

- Stoichiometric Ratio
- Fabric Filter Flue Gas Temperature
- Air-to-Cloth Ratio
- Fabric Filter Inlet SO_2 Concentration
- Recycle Ratio
- Fabric Filter Pressure Drop

Range of Variables

Lime-Only

The range of variables investigated in the pilot tests using a lime-only mode of operation is shown in Table 5.8. The range studied was dictated more by fabric filter operational considerations than by SO_2 removal requirements.

TABLE 5.8 RANGE OF FABRIC FILTER VARIABLES INVESTIGATED LIME-ONLY OPERATION

Variable	Minimum	Maximum
Stoichiometric Ratio, moles $Ca(OH)_2$/mole SO_2 inlet	0.5	5.9
Fabric Filter Inlet Temperature, °F	139	215
Fabric Filter Outlet Temperature, °F	127	183
Approach to Adiabatic Saturation Temperature, °F	7	63
Air-to-Cloth Ratio, ft/min	1.33	2.74
Fabric Filter Inlet SO_2 Concentration, ppmv	140	1850
Fabric Filter Pressure Drop, in. H_2O	0.5	8.0
Number of Bags in Fabric Filter	20	24

Recycle

The range of variables investigated in the pilot test program using recycle operation is shown in Table 5.9.

TABLE 5.9 RANGE OF FABRIC FILTER VARIABLES INVESTIGATED RECYCLE OPERATION

Variable	Minimum	Maximum
Stoichiometric Ratio, moles $Ca(OH)_2$/mole SO_2 inlet	0.7	6.4
Fabric Filter Inlet Temperature, ^{o}F	144	210
Fabric Filter Outlet Temperature, ^{o}F	125	178
Approach to Adiabatic Saturation Temperature, ^{o}F	7	61
Recycle Ratio, lb recycle solids/lb fresh lime	0	3.2
Air-to-Cloth Ratio, ft/min	1.38	2.80
Fabric Filter Inlet SO_2 Concentration, ppmv	40	1160
Fabric Filter Pressure Drop, in. H_2O	0.5	8.0
Number of Bags in Fabric Filter	20	24

Stoichiometric Ratio

For fabric filter data correlating purposes, stoichiometric ratio is defined as the moles of fresh $Ca(OH)_2$ entering the spray dryer per mole of SO_2 entering the system. This stoichiometry is not the same as the fabric filter actually "sees". Reaction in the spray dryer reduces both the $Ca(OH)_2$ and SO_2 content to the fabric filter. However, calculation of an actual stoichiometry based on fabric filter inlet conditions is more complicated and may not be generally useful as a fabric filter design parameter. A stoichiometry based on the lime slurry and flue gas feeds to the dry scrubbing system is more practical and was found to correlate well with SO_2 removal.

Lime-Only

Percent SO_2 removal in the fabric filter correlates well with fresh lime stoichiometry fed to the spray dryer. SO_2 removal increases directly with increasing fresh lime stoichiometry, as Figure 5-22 shows. The spray dryer stoichometry reflects the stoichiometry, based on unreacted lime and SO_2 from the spray dryer, fed to the fabric filter. SO_2 removal efficiency in the fabric filter is based on the inlet and outlet flue gas SO_2 concentrations.

Recycle

SO_2 removal in the fabric filter increases linearly with fresh lime stoichiometric ratio, as Figure 5-24 shows. Fabric filter SO_2 removal is negligible up to a stoichiometry of about 0.75 and then increases sharply to attain a value of about 50 percent at an SR = 1.5.

At a fabric filter operating temperature of 175^{o}F, increasing the stoichiometric ratio from 1.0 to 2.1 increases fabric filter SO_2 removal by about 10 percent when the other process variables are held constant (Figure 5-23).

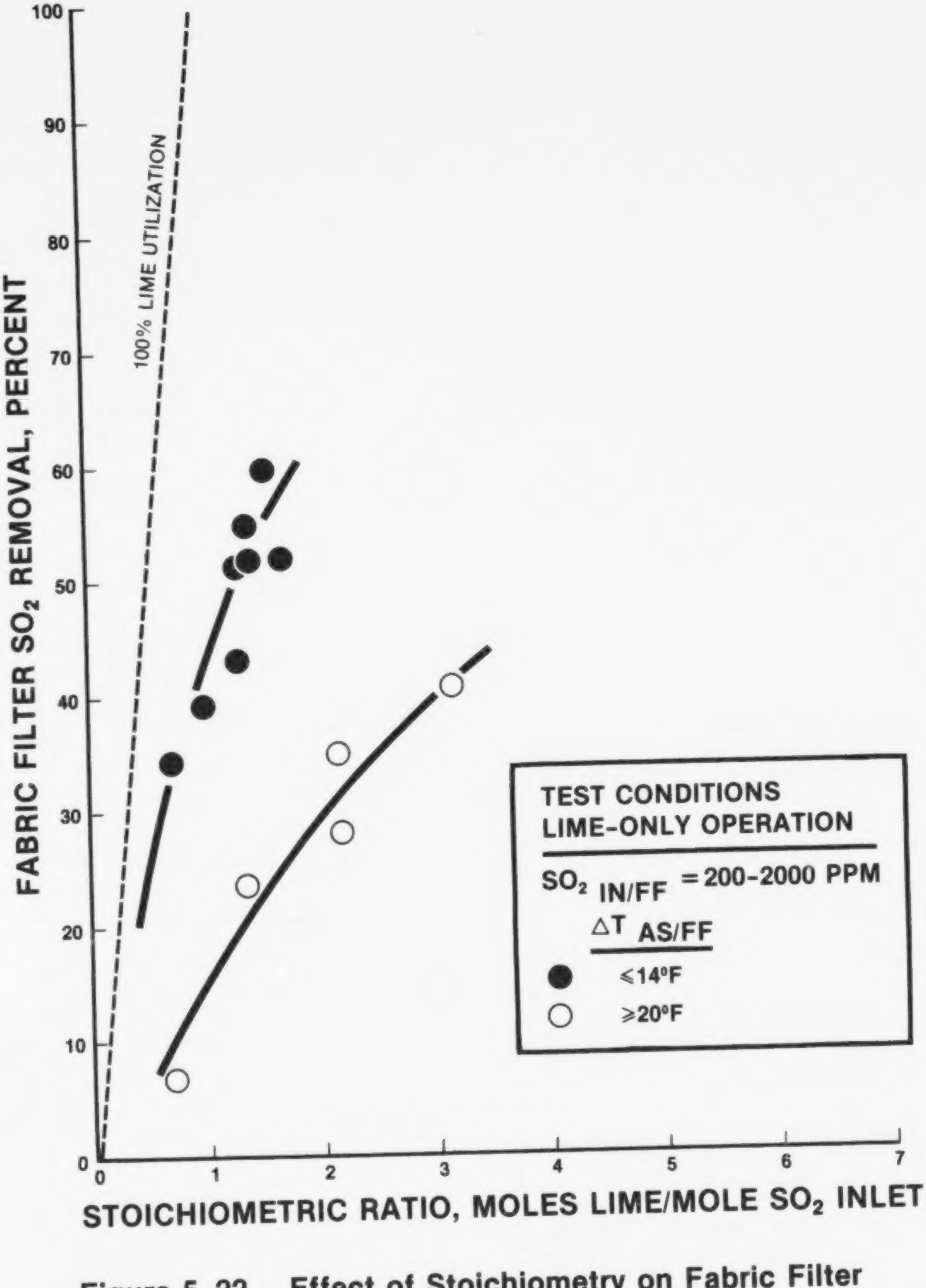


Figure 5-22. Effect of Stoichiometry on Fabric Filter SO_2 Removal - Lime-Only Operation.

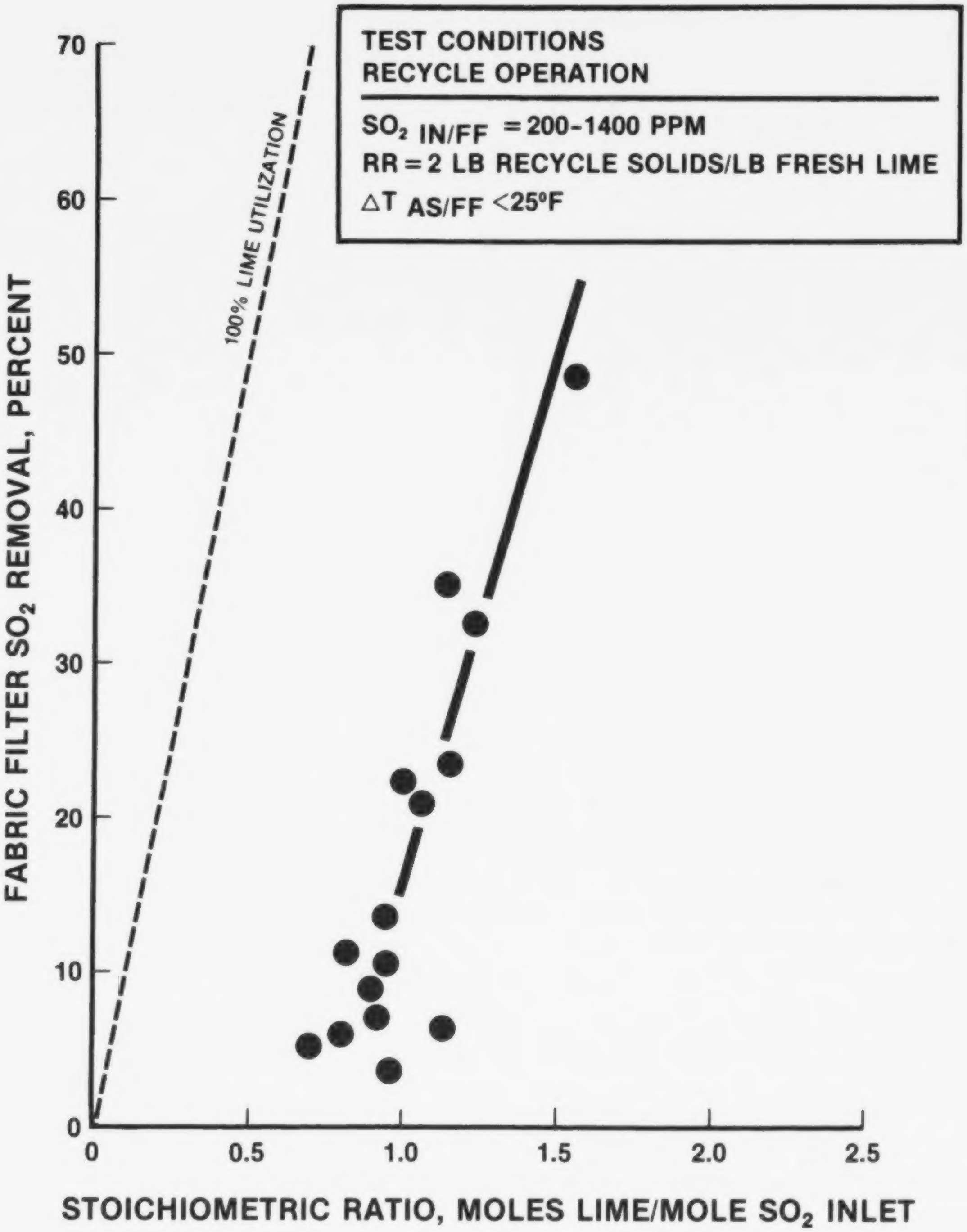


Figure 5-23. Effect of Stoichiometry on Fabric Filter SO_2 Removal - Recycle Operation.

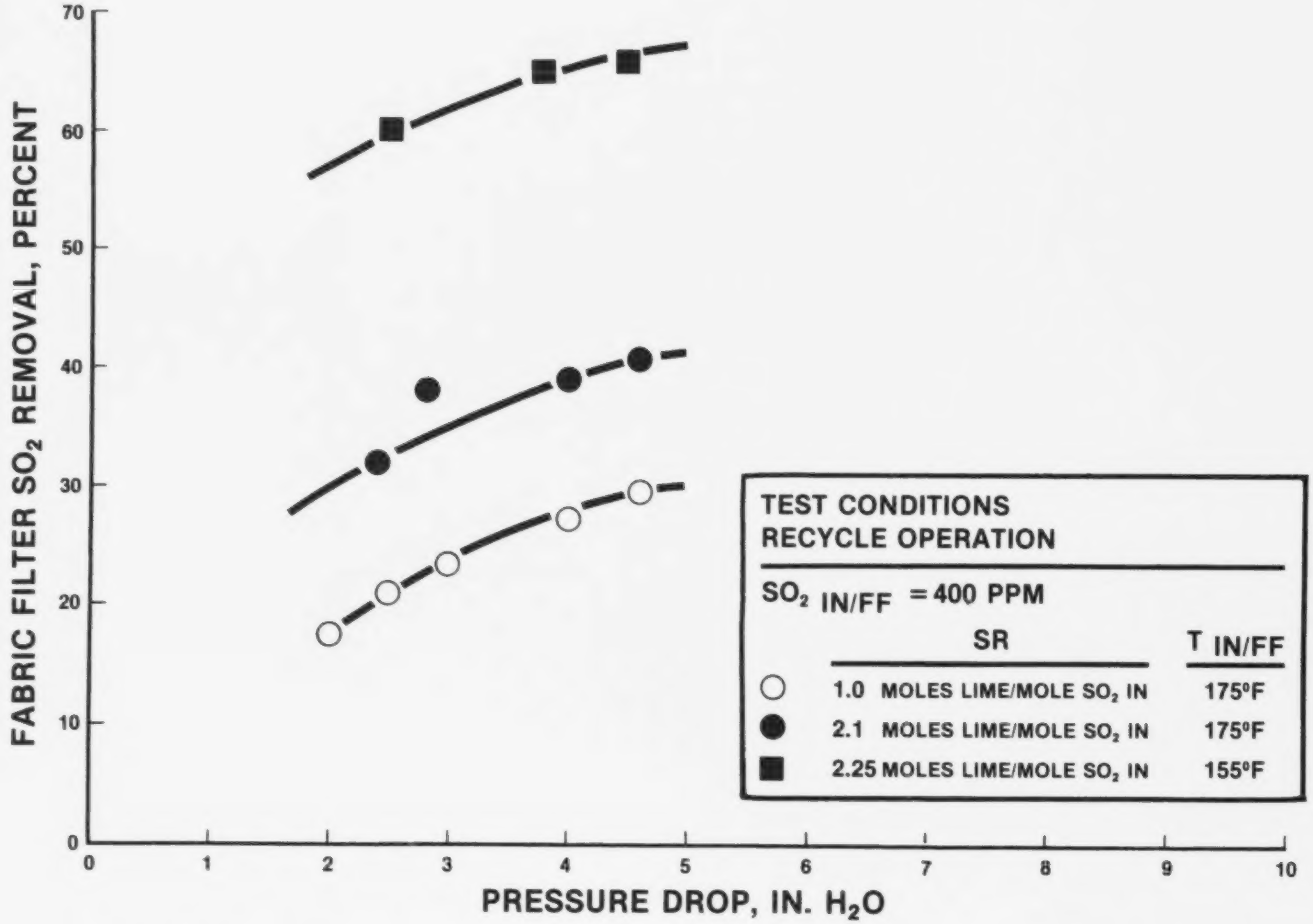


Figure 5-24. Effect of Pressure Drop on Fabric Filter SO_2 Removal.

Fabric Filter Flue Gas Temperature

Lime-Only

Pilot plant tests were conducted at various levels of fabric filter flue gas temperature. A strong inverse temperature effect on SO_2 removal was observed when operating at low fabric filter inlet temperature, approaching the adiabatic saturation temperature, as shown in Figure 5-22. As the flue gas temperature approaches adiabatic saturation, the solids moisture content increases resulting in a rapid increase in SO_2 removal efficiency.

Approach to the adiabatic saturation temperature is based on the fabric filter outlet temperature, ($\Delta T_{AS/FF} = T_{OUT/FF} - T_{AS/FF}$). Note that the adiabatic saturation temperature at the fabric filter outlet is not the same as that at the spray dryer outlet. Hot gas bypass (when utilized) and cold air leakage affect the value for $T_{AS/FF}$. These factors were recognized and accounted for in our calculations for the pilot test runs.

Temperature drop across the fabric filter (ΔT_{FF}) is a function of the heat loss from the baghouse. Heat loss in the fabric filter was governed by ambient temperature and the wind conditions at Comanche. Most of the heat loss occurred at the uninsulated inlet plenum to the fabric filter since the fabric filter unit itself is insulated. Temperature drops through the fabric filter ranged from 5 to 15°F during the test progam.

Recycle

As observed for the spray dryer, SO_2 removal in the fabric filter is strongly influenced by the flue gas temperature and its proximity to the adiabatic saturation temperature. Figure 5-25 shows that SO_2 removal strongly increases as $\Delta T_{AS/FF}$ decreases. Higher SO_2 removal near adiabatic saturation apparently is related to the higher moisture content of the reactant solids in the fabric filter. SO_2 removal is favored by keeping the lime particles as wet as possible for as long as possible.

At operating temperatures greater than 160°F and at stoichiometries <1.5, very little SO_2 removal ($<5\%$) occurs in the fabric filter (Figure 5-26). The poor SO_2 removal experienced is not unexpected since the flue gas in the fabric filter is at least 45°F above the adiabatic saturation temperature and the solids are quite dry. Moisture content of the solids collected from the fabric filter under these conditions ranged from 1.8 to 3.6 percent H_2O.

Even though SO_2 removal within the fabric filter is favored by lower operating temperatures, it is often desirable to maintain the temperature at a higher value to avoid condensation, corrosion, bag blinding, and low buoyancy conditions in the stack. As a consequence, relatively less SO_2 removal takes place in the fabric filter at higher temperature conditions.

In certain applications, the simultaneous constraints of low spray dryer outlet temperature and high fabric filter inlet temperature may require reheat of the flue gas between the units. Flue gas reheat can be accomplished either by partial bypass of hot gas around the dryer and/or by external methods, e.g., steam heat exchanger.

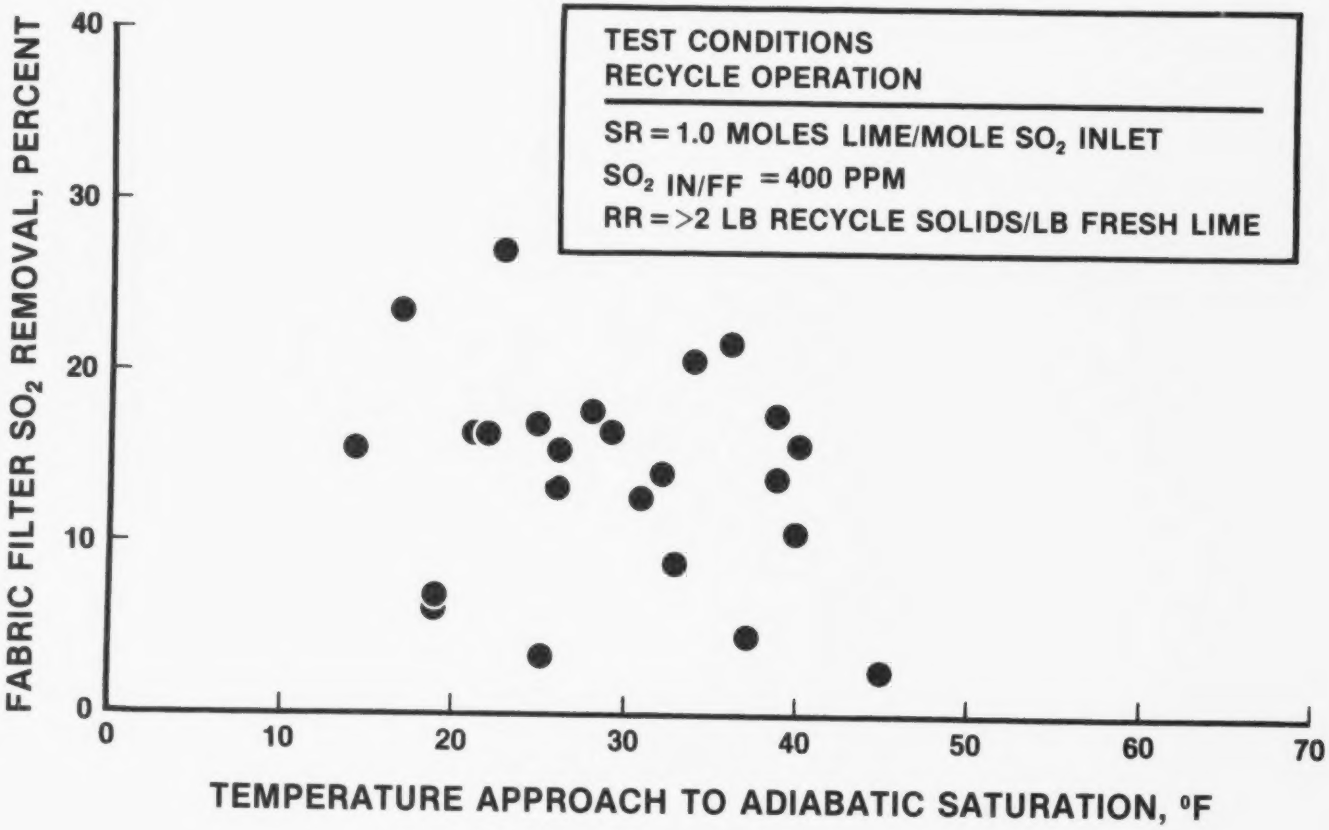


Figure 5-25. Effect of Adiabatic Saturation Temperature on Fabric Filter SO_2 Removal.

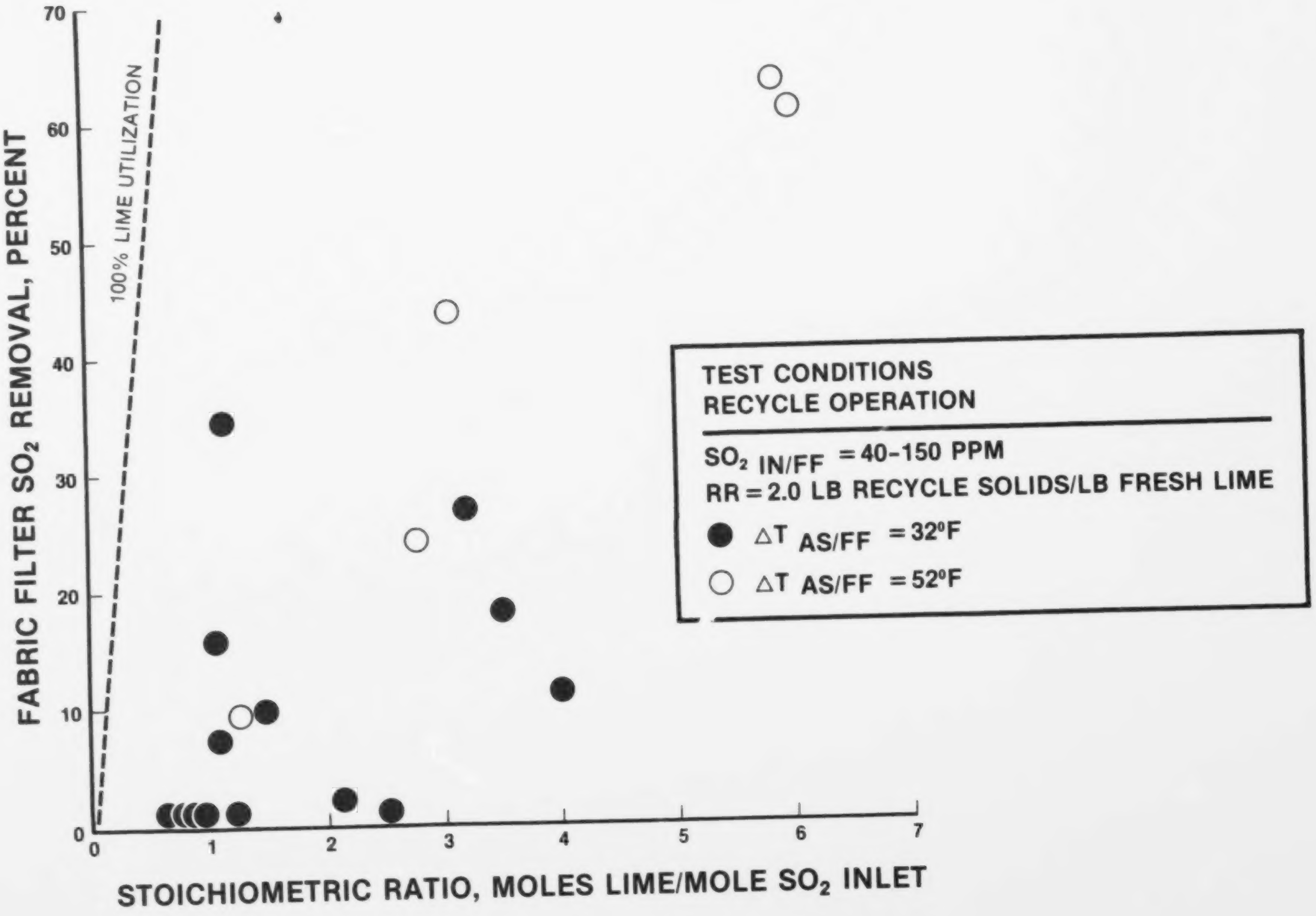


Figure 5-26. Effect of Adiabatic Saturation Temperature and Stoichiometry on Fabric Filter SO_2 Removal.

Recycle Ratio

Figure 5-27 shows that recycling product solids enhances SO_2 removal across the fabric filter. SO_2 removal values up to 30 percent were achieved in the fabric filter as the recycle ratio was increased up to 2.0 - 2.5 lb recycle solids/lb fresh lime. As observed in the spray dryer, increasing the recycle ratio beyond 2.5 lb recycle solids/lb fresh lime provided no additional benefit to SO_2 removal.

Air-to-Cloth Ratio

The economic range of interest of air-to-cloth ratio in a utility fabric filter is about 2.0 to 2.5 ft/min. using fiberglass bags. Air-to-cloth ratio is based on fabric filter inlet conditions and is defined as the actual volume of flue gas into the baghouse divided by the total bag surface area.

Lime-Only

Air-to-cloth ratio was found to have a negligible effect on SO_2 removal in the fabric filter, as shown in Figure 5-28. Although most of the pilot tests were performed at air-to-cloth ratios in the vicinity of 2.0 ft/min., the parameter was studied over the range between 1.3 and 2.5 ft/min. Table 5.10 presents a summary of pertinent operating conditions for the runs shown in Figure 5-28.

TABLE 5.10 EFFECT OF AIR-TO-CLOTH RATIO ON FABRIC FILTER SO_2 REMOVAL

Run No.	Air-To-Cloth Ratio (ft/min)	Stoichiometric Ratio (moles lime/mole SO_2 inlet)	Fabric Filter Inlet Temperature (^oF)	Fabric Filter SO_2 Removal (%)
219	2.3	1.08	179	12.0
501R	2.1	1.04	176	15.0
504	1.8	0.96	179	12.5
509	1.8	1.00	178	13.0
507	2.9	0.98	176	14.0
508	2.1	0.99	177	9.0
508R	2.2	1.04	179	13.0
827	2.3	1.06	178	9.8

Recycle

The range of air-to-cloth ratios investigated in the test work extended from 1.38 to 2.80 ft/min for the recycle runs. The pilot plant data show no significant correlation between SO_2 removal across the fabric filter and air-to-cloth ratio (Figure 5-29).

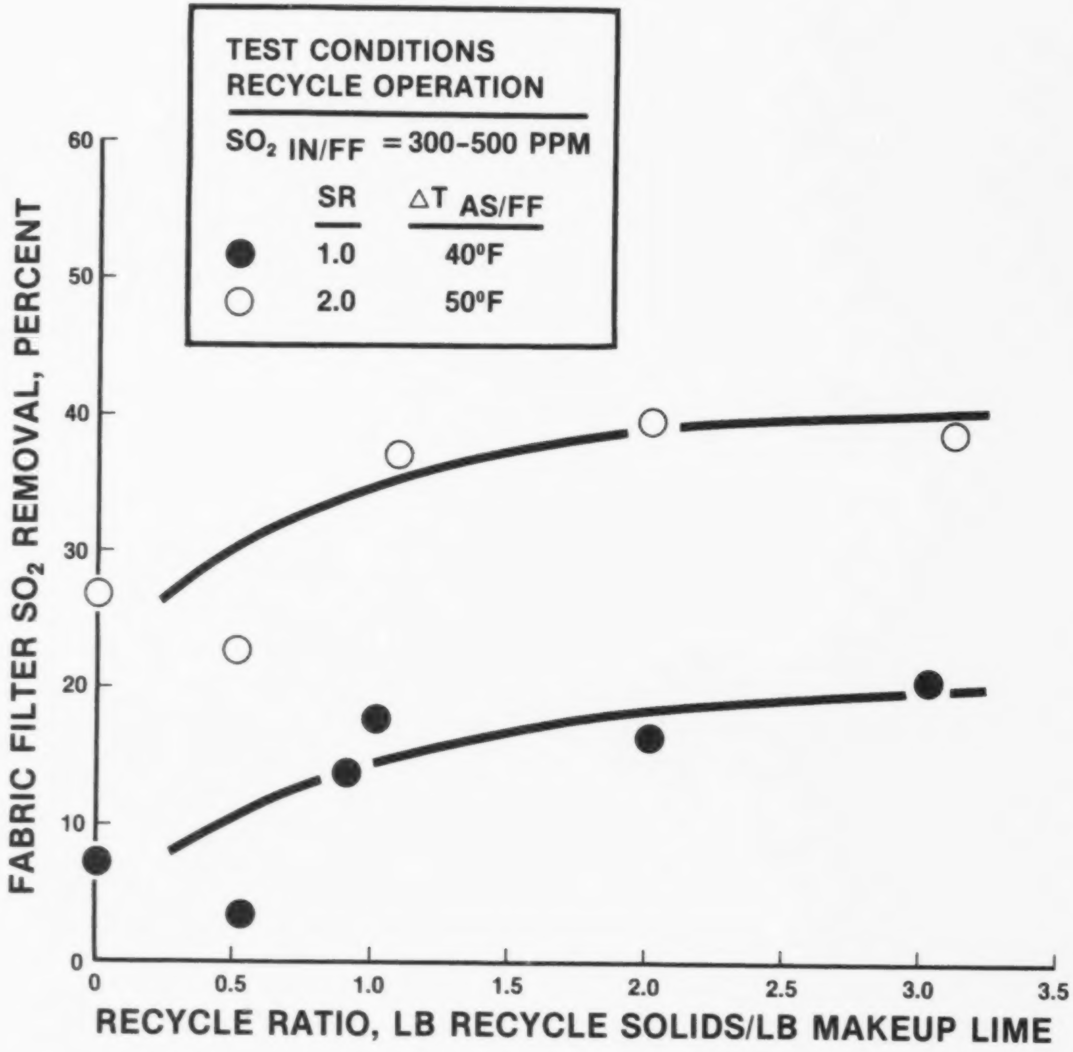


Figure 5-27. Effect of Recycle Ratio on Fabric Filter SO_2 Removal.

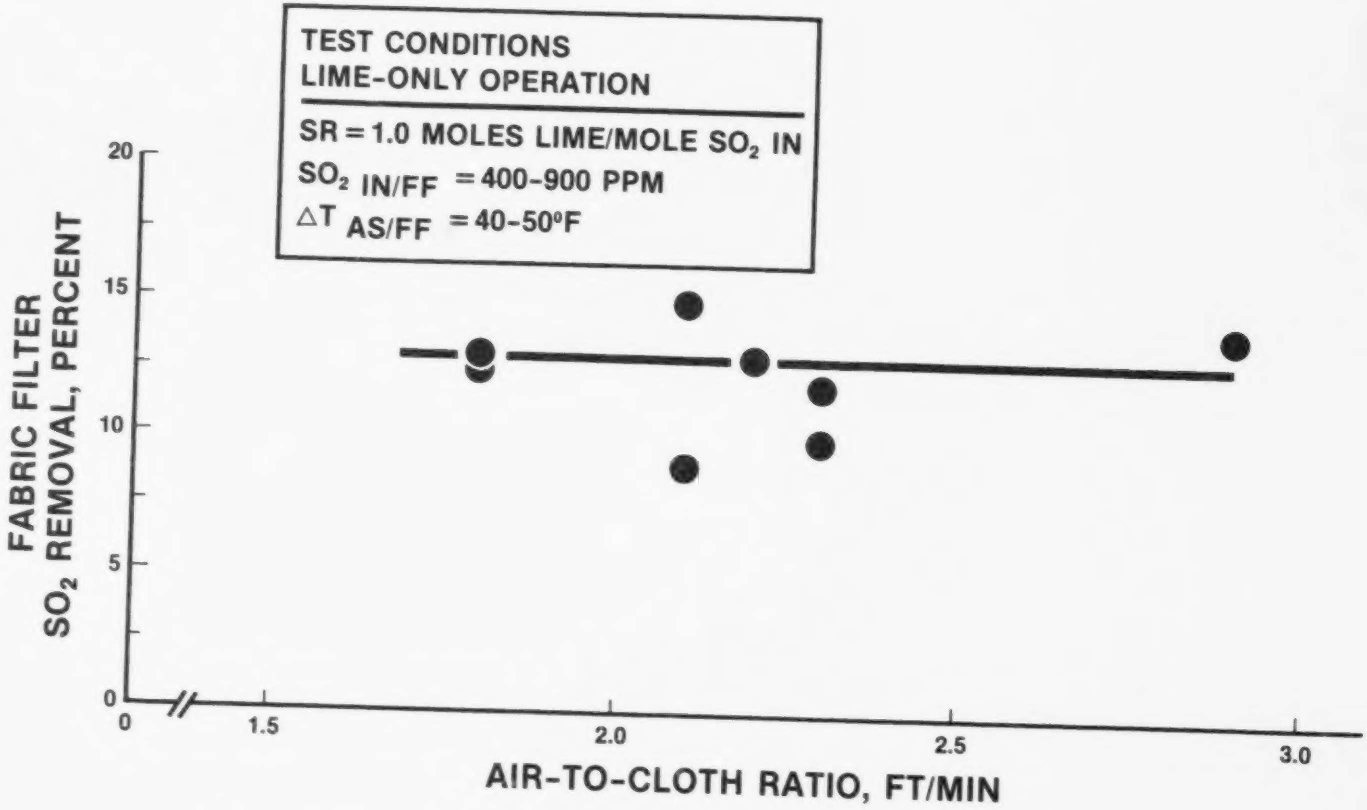


Figure 5-28. Effect of Air-to-Cloth Ratio on Fabric Filter SO_2 Removal - Lime-Only Operation.

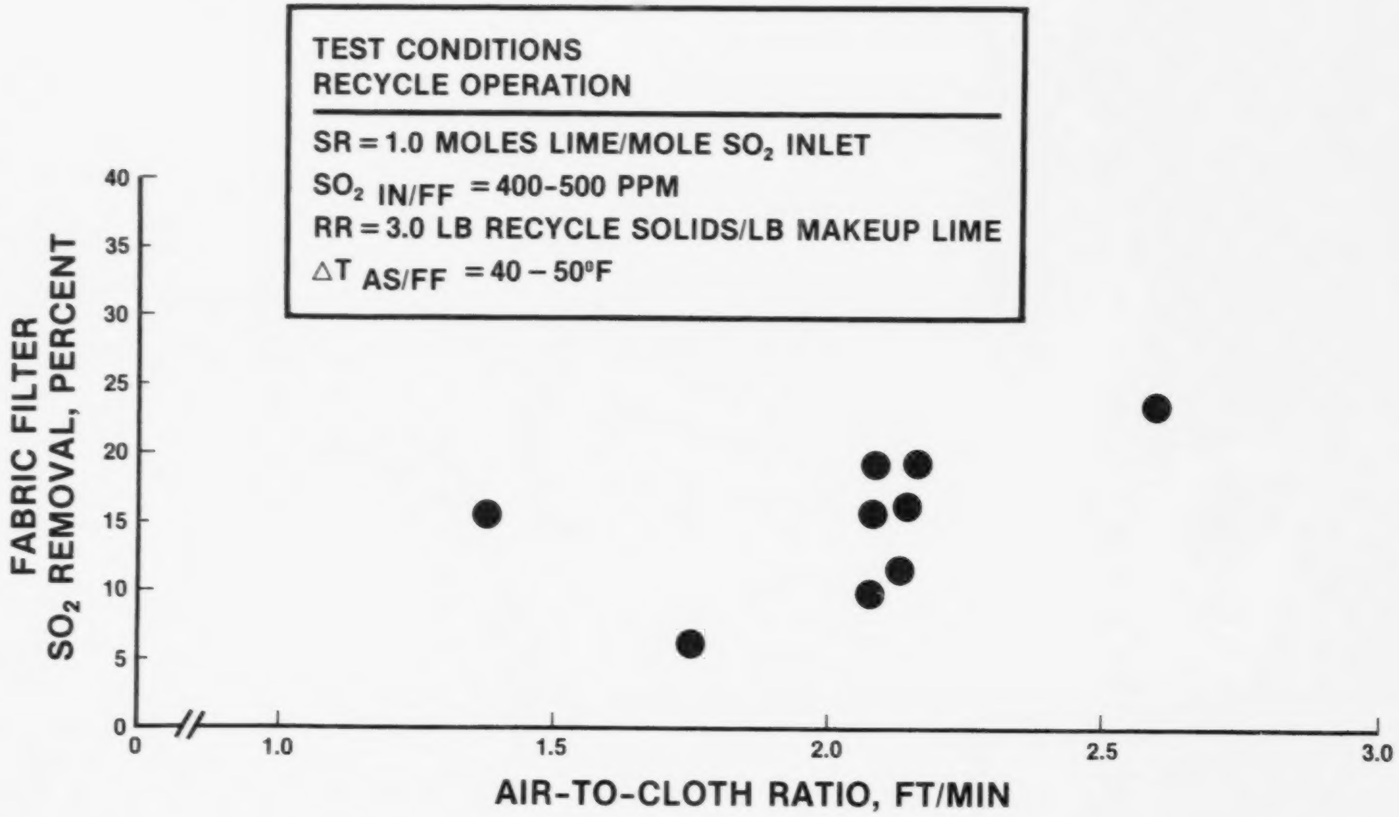


Figure 5-29. Effect of Air-to-Cloth Ratio on Fabric Filter SO_2 Removal - Recycle Operation.

Flue Gas Inlet SO_2 Concentration

Lime-Only

SO_2 removal in the fabric filter is unaffected by the SO_2 concentration in the inlet flue gas to the fabric filter. Figure 5-30 shows the insensitivity of fabric filter SO_2 removal to inlet SO_2 concentration in the range from about 400 to 1300 ppm SO_2. At the operating conditions of the lime-only tests, SR ∼ 1.0 and fabric filter inlet temperature of ∼ 180°F, SO_2 removal values of only about 10 percent were achieved across the fabric filter.

Recycle

Although a wide range of experimental conditions was investigated, the pilot plant data show no significant correlation between inlet SO_2 concentration to the fabric filter and SO_2 removal in the fabric filter. Figure 5-31 presents the pilot test results under recycle operation at a recycle ratio of 3.0. In the course of the test program, inlet SO_2 concentrations to the fabric filter covered the range from 40 to 1160 ppmv. The SO_2 concentration at the fabric filter inlet was not controlled directly, but was a consequence of the extent of SO_2 removal accomplished in the spray dryer and any contribution from untreated gas bypassed around the spray dryer.

Fabric Filter Pressure Drop

Particulate collection in the fabric filter during dry SO_2 scrubbing produces an accumulation with time of the flyash/FGD solids mixture on the filter cloth during an operating cycle. The thickness and nature of this layer of collected solids is reflected by the pressure drop of the flue gas as it flows through the bed. From an initial value, the pressure drop increases with time as the layer of solids builds up. At a pre-set maximum value for the pressure drop, a reverse air cleaning cycle is automatically initiated. The accumulated solids are dislodged and the pressure drop returns to a lower value. If the cleaning method is adequate under the existing operating conditions, the pressure drop returns to its initial value.

Lime-Only

Fabric filter SO_2 removal varies not only with the key process variables, stoichiometric ratio and temperature, but also with time between cleaning cycles. After reverse air cleaning of the filter bags, fabric filter pressure drop (ΔP) and SO_2 removal increase with time during an operating cycle. Figure 5-23 presents SO_2 removal in the fabric filter as a function of the ΔP increase during different operating cycles. Initially SO_2 removal tends to increase linearly with pressure drop but then begins to level off at higher ΔP values near the end of the cleaning cycle. As Figure 5-23 shows, the pressure drop increased from about 2.0 in. H_2O initially to between 4 and 5 in. H_2O at the end of operating cycles of 60 to 90 minutes duration.

Fabric filter pressure drop is not expressed as an explicit variable in the regression analyses performed relating SO_2 removal to baghouse process parameters. An average value of SO_2 removal in the fabric filter was used for quantitative correlation of performance with the significant process variables. The dynamic, or unsteady-state, nature of pressure drop during the course of a test run at otherwise continuous, steady-state conditions contri-

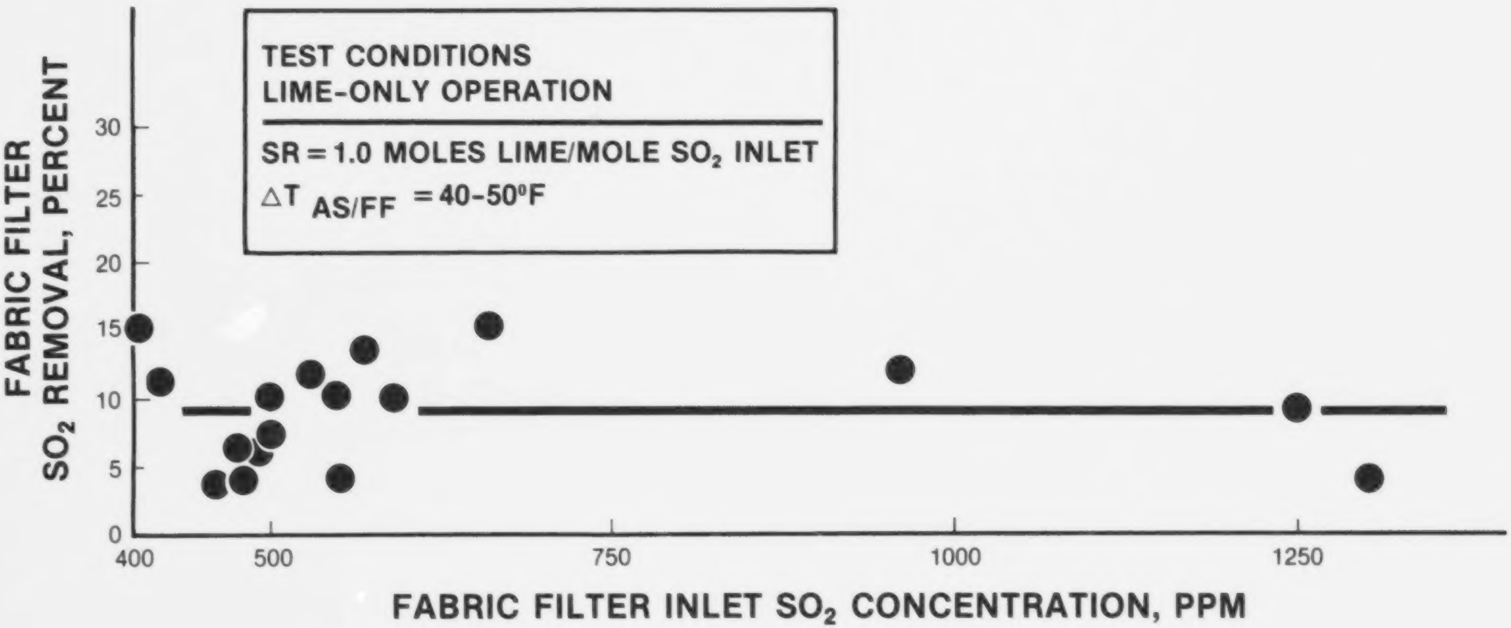


Figure 5-30. Effect of Inlet SO_2 Concentration on Fabric Filter SO_2 Removal - Lime-Only Operation.

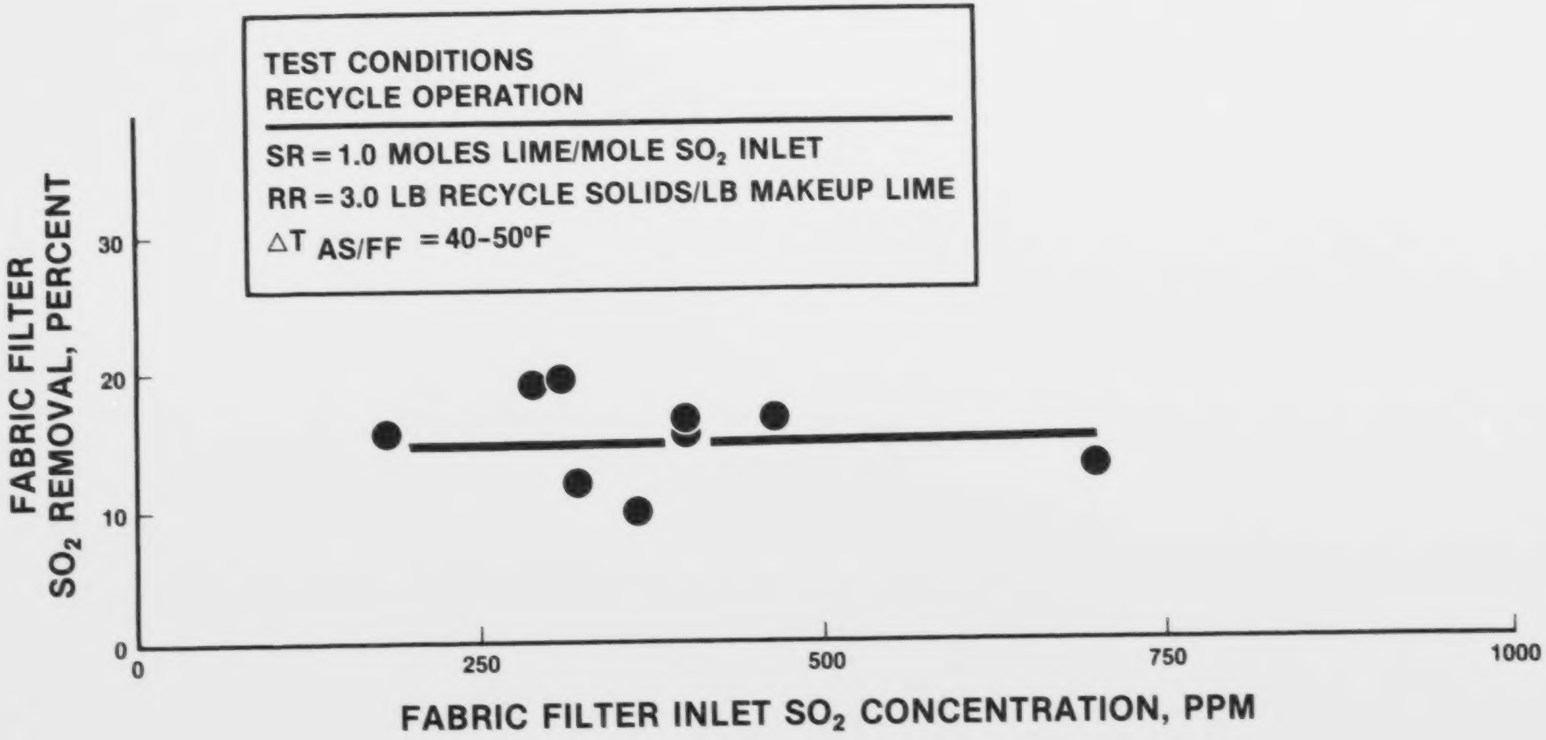


Figure 5-31. Effect of Inlet SO_2 Concentration on Fabric Filter SO_2 Removal - Recycle Operation.

buted to a greater degree of fabric filter data scatter compared to the spray dryer SO_2 removal results .

Recycle

Observations during the recycle mode of operation of the pilot tests showed the linear, or nearly linear, increase in SO_2 removal as the pressure drop builds up during operation between cleaning cycles. Although a wide range of values was encountered during the course of the pilot test program (ΔP_{FF} = 0.5 - 8 in. H_2O), the pressure drop difference between initial level and the level required to trigger a cleaning cycle was generally limited to about 2 in. H_2O. Restricting the allowed variation in ΔP_{FF} for a given run helps to minimize the variation in SO_2 removal across the fabric filter for a particular run.

The increase in pressure drop across the fabric filter with time is affected by grain loading of the mixture of flyash and FGD solids in the flue gas, air-to-cloth ratio, and temperature approach to adiabatic saturation. At the Comanche Station, the flyash grain loading typically was measured at about 2 gr/dscf. FGD solids grain loading varies with system operating conditions that include inlet SO_2 level and stoichiometric ratio.

Pressure drop across the fabric filter is also affected by operating temperature or approach to adiabatic saturation. As the fabric filter flue gas temperature approaches the adiabatic saturation temperature, the moisture content of the particulate layer increases. At low operating temperatures in the fabric filter ($\Delta T_{AS/FF} < 25^{o}F$), the pressure drop increases markedly. Also, reverse air cleaning is often no longer sufficient to return the operating pressure drop to its initial level. More drastic cleaning methods (e.g., shaking) are sometimes required during low temperature operation of the fabric filter.

The presence of a cementitious flyash, such as that at Comanche Station, makes low temperature operation of the baghouse particularly difficult. When the operating temperature of the baghouse is kept high ($\Delta T_{AS/FF} > 50^{o}F$), these problems tend to be alleviated. For example, pressure drop across the baghouse ranged from 2.0 to 4.0 in. H_2O and was very steady throughout the 5-day continuous demonstration run. No variation at all was observed in the value of initial pressure drop for each cleaning cycle as it remained at 2.0 in. H_2O during the demonstration test. Time between cleaning cycles generally varied between 60 to 80 minutes, but no trend was found. Thus quite satisfactory fabric filter performance and operation occurred during the 5-day demonstration test at fabric filter inlet temperatures in the range of 200°F.

Fabric Filter SO_2 Removal Correlations

Lime-Only

In developing a correlation to predict SO_2 removal in the fabric filter, the following parameters were found to be statistically significant and to dominate fabric filter SO_2 performance employing once-through, lime-only operating conditions (no recycle):

- Stoichiometric Ratio (SR)

- Approach to Adiabatic Saturation Temperature ($\Delta T_{AS/FF}$)

A total of 100 lime-only runs was examined to develop the empirical equation correlating fabric filter SO_2 removal with SR and $\Delta T_{AS/FF}$. The ranges of these parameters follow:

Variables	Range
SR (moles $Ca(OH)_2$/mole SO_2 in)	0.56 - 5.9
$\Delta T_{AS/FF}$ (°F)	10 - 43

Fabric filter SO_2 removal is correlated as follows:

$$\text{Fabric Filter } SO_2 \text{ Removal, \%} = 38.68 + 10.26\,(SR) - 1.16\,(\Delta T_{AS/FF}) \qquad (5\text{-}9)$$

For Equation (5-9), the multiple correlation coefficient is 0.87 and standard error of estimate is 7.4. A comparison of fabric filter SO_2 removals actually achieved in the pilot tests with their predicted values from Equation (5-9) is plotted in Figure 5-32. The fabric filter SO_2 performance correlation does not predict SO_2 removal as well as the spray dryer correlation.

Several sources of variability come into play in the fabric filter operation which contributed to the data scatter in the pilot test runs. First, the inherent variation in SO_2 level in the flue gas to the dry scrubbing system at Comanche is relatively large compared to the fabric filter SO_2 concentrations measured. Secondly, the fabric filter pressure drop (ΔP) is continually varying during operating cycle reflecting changes in the filter cake thickness. Finally, while spray dryer operating conditions were fixed for a test since they were the independent variables, fabric filter operating parameters generally were not pre-set and varied more widely as a result.

Recycle

SO_2 removal across the fabric filter was correlated to the significant independent variables of the dry scrubbing system for recycle operation. The data used for the fabric filter SO_2 correlation consist of 76 pilot plant tests. The detailed operating conditions are presented in Appendix A.

The resulting empirical equation is:

$$\begin{aligned}\text{Fabric Filter } SO_2 \text{ Removal, \%} &= 39.56(SR) - 4.89(SR)^2 - 13.52(RR) + 3.88(RR)^2 - 0.55(\Delta T_{AS/FF}) \\ &\quad + 0.005(\Delta T_{AS/FF})^2 \qquad (5\text{-}10)\end{aligned}$$

where

SR = Stoichiometric Ratio (moles lime/mole SO_2 into spray dryer)

RR = Recycle Ratio (lb recycle solids/lb fresh lime)

$\Delta T_{AS/FF}$ = Fabric Filter Temperature Approach to Adiabatic Saturation (°F)

Equation (5-10) accounts for 80.6 percent of the variation in SO_2 removal across the fabric filter with a standard error of 11.47 percent (absolute).

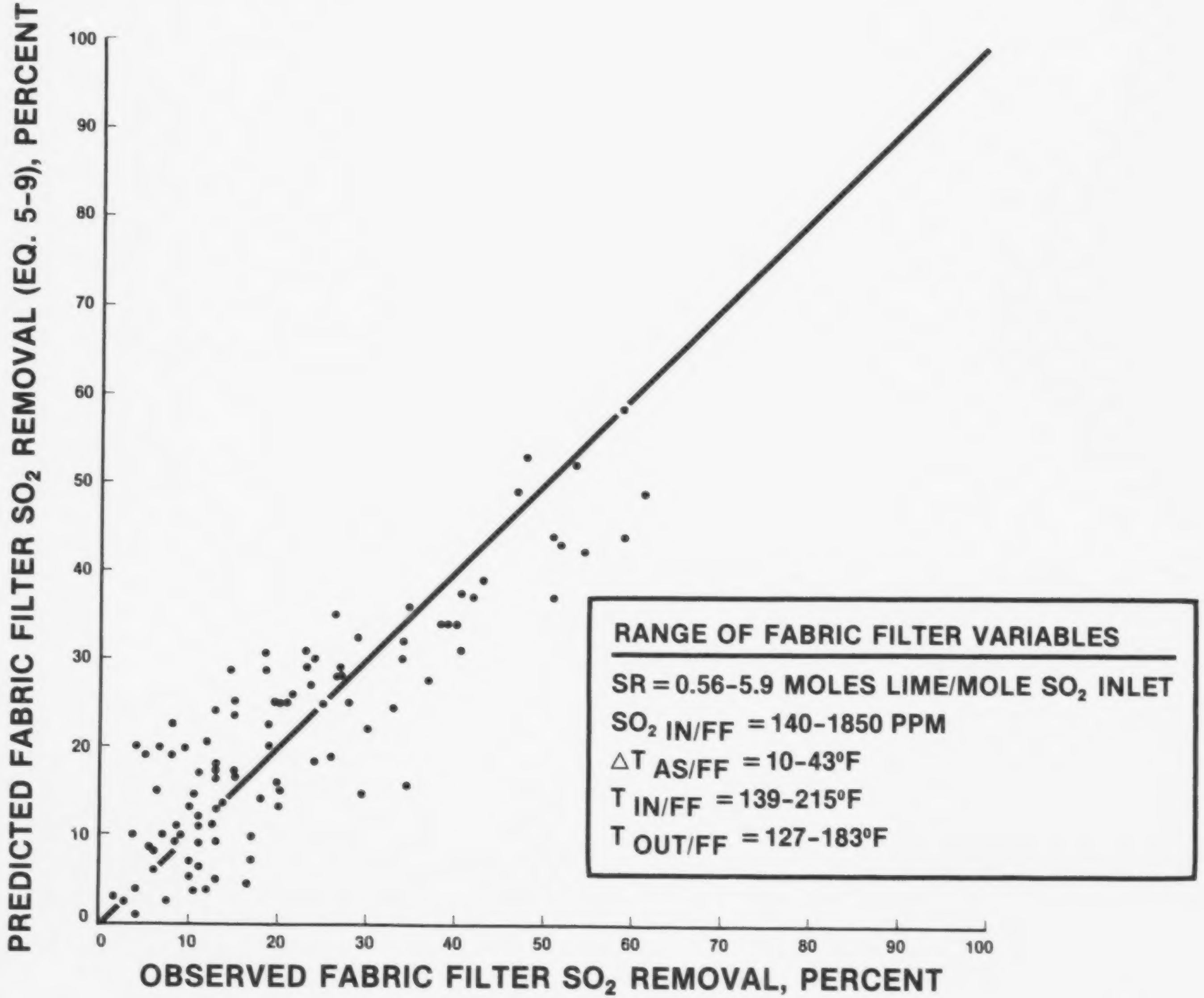


Figure 5-32. Parity Plot of Observed and Predicted Fabric Filter SO_2 Removal - Lime-Only Operation.

Figure 5-33 is a parity plot which the compares observed SO_2 removal in the fabric filter with SO_2 removal predicted by Equation (5-10).

OVERALL SO_2 REMOVAL

The dry scrubbing system consists of a spray dryer followed by a fabric filter to achieve simultaneous control of SO_2 and particulate emissions. The spray dryer is the key SO_2 removal device in the dry scrubbing system. At the conditions tested in the pilot plant, at least 75 percent of the total SO_2 removal in the dry scrubbing system is accomplished in the spray dryer (see Figure 5-34). In Figure 5-34, spray dryer SO_2 removal relative to the total of spray dryer and fabric filter SO_2 removal is plotted versus stoichiometry. Lime stoichiometry, spray dryer operating temperature, and fabric filter operating temperature are the key variables that determine relative SO_2 removal. The spray dryer and fabric filter operating temperatures, of course, are related to their respective correlating parameters, $\Delta T_{AS/SD}$ and $\Delta T_{AS/FF}$.

High fabric filter operating temperature reduces SO_2 removal in the fabric filter and, therefore, increases SO_2 removal in the spray dryer relative to total SO_2 removal. As the fabric filter inlet temperature is increased from 145°F to 200°F, spray dryer SO_2 removal increases from 80 to 90 percent to greater than 95 percent of the total (Figure 5-34). Since SO_2 removal depends strongly upon the particle moisture content, the relative SO_2 removal results presented in this report are related to the specific test conditions used, including the flue gas reheat method. Flue gas leaving the spray dryer was reheated before entering the fabric filter by warm gas by-passed around the spray dryer.

Lime-Only

In order to predict overall SO_2 removal in the dry SO_2 scrubbing system, the correlations developed for spray dryer SO_2 removal and the fabric filter SO_2 removal can be applied using the following relationship:

$$\begin{matrix}\text{Overall} \\ SO_2\ \text{Removal, \%}\end{matrix} = \begin{matrix}\text{Spray Dryer} \\ SO_2\ \text{Removal, \%}\end{matrix} + \left[100 - \begin{matrix}\text{Spray Dryer} \\ SO_2\ \text{Removal, \%}\end{matrix}\right] \times \left[\begin{matrix}\text{Fabric Filter} \\ \dfrac{SO_2\ \text{Removal,\%}}{100}\end{matrix}\right] \qquad (5\text{-}11)$$

where the spray dryer and the fabric filter percentage SO_2 removals are calculated employing the following correlations:

$$\begin{matrix}\text{Spray Dryer} \\ SO_2\ \text{Removal, \%}\end{matrix} = -14.1 + 14.26(SR) - 1.32(SR)^2 + 12.8(T) - 0.53(T)^2 \qquad (5\text{-}12)$$

$$\begin{matrix}\text{Fabric Filter} \\ SO_2\ \text{Removal, \%}\end{matrix} = 38.68 + 10.26(SR) - 1.16\ (\Delta T_{AS/FF}) \qquad (5\text{-}13)$$

$$\text{where}\quad T = 1 + \frac{\Delta T_{SD}}{\Delta T_{AS/SD}} \qquad (5\text{-}14)$$

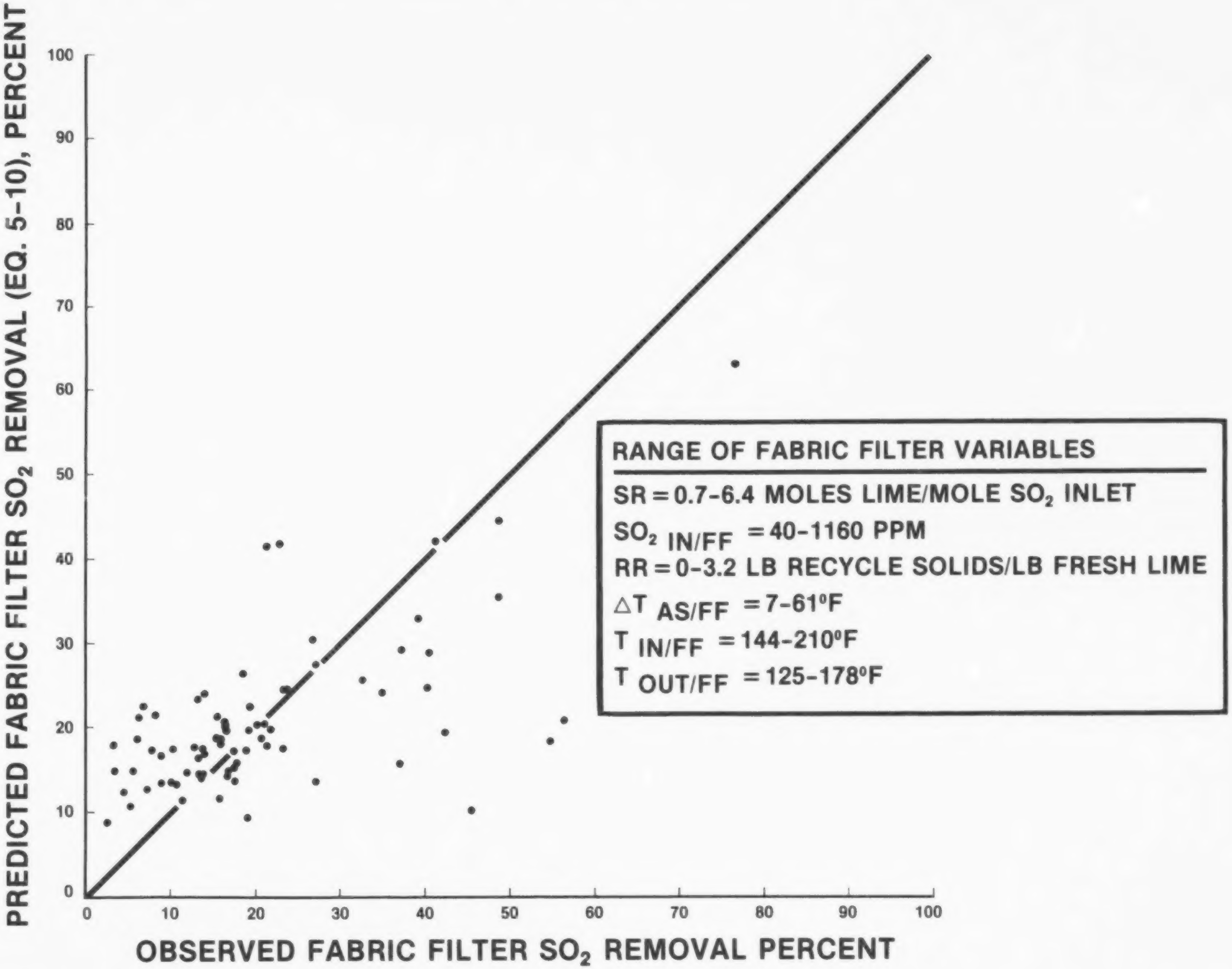


Figure 5-33. Parity Plot of Observed and Predicted Fabric Filter SO_2 Removal - Recycle Operation.

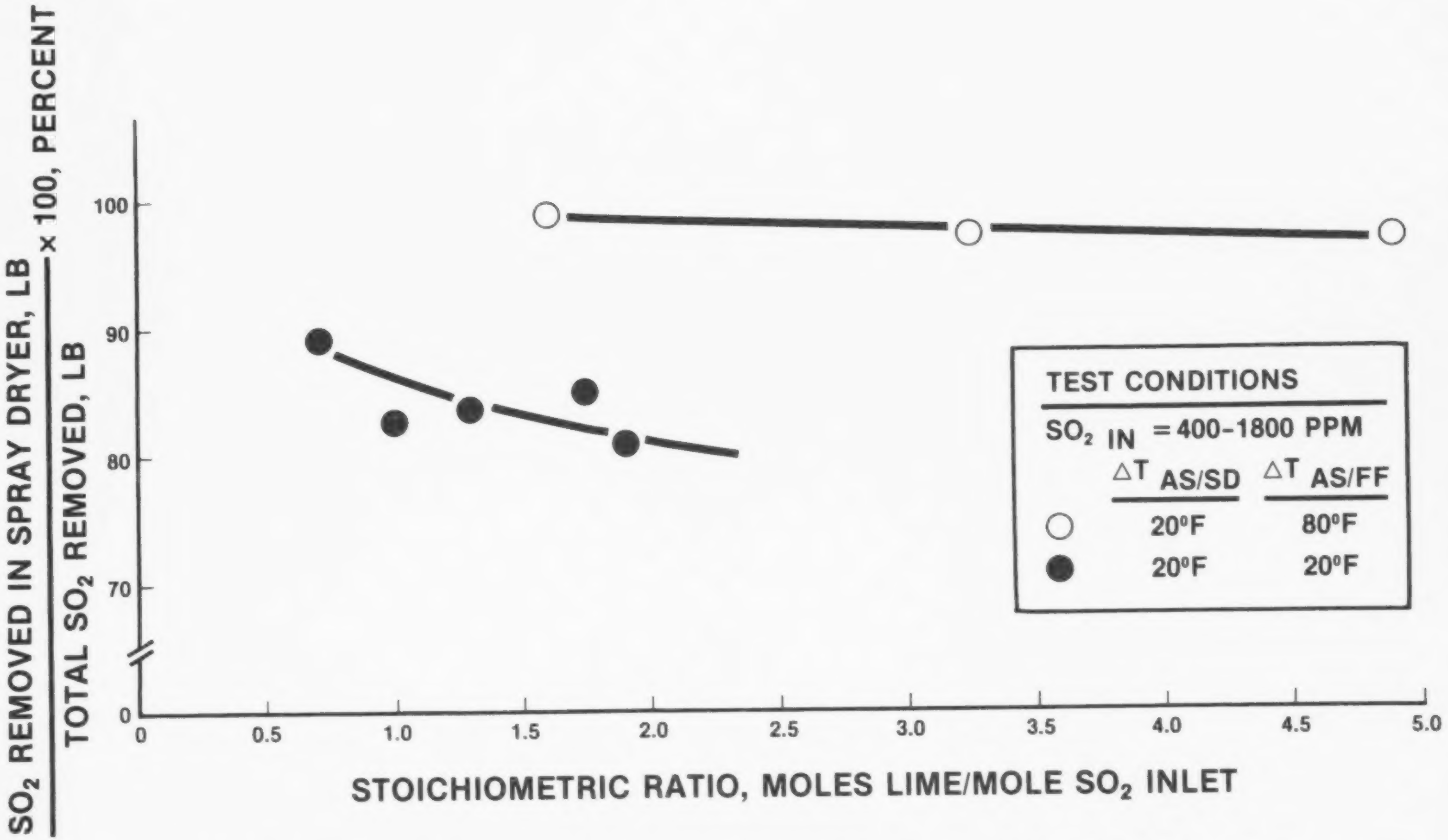


Figure 5-34. SO_2 Removal in Spray Dryer Relative to Total SO_2 Removal.

Overall SO_2 removals actually attained in the pilot tests and those predicted by the above correlations are presented in the parity plot of Figure 5-35. As Figure 5-35 illustrates, good agreement is achieved between the actual SO_2 removal and predicted overall SO_2 removal using the correlations (standard error of estimate = 5.5). Overall SO_2 removal in the dry scrubbing system is plotted in Figure 5-36 for various values of $\Delta T_{AS/SD}$, ΔT_{SD}, and stoichiometric ratio. In this plot, the correlations predict overall SO_2 removal quite well over most of the range of conditions. However, they tend to underpredict SO_2 removal by about 3 to 5 percent at high levels of SO_2 removal where the approach to adiabatic saturation temperature is low.

Recycle

Overall SO_2 removal in the dry scrubbing system in the range of 50 to 90 percent is achievable utilizing recycle operation, as Figure 5-37 indicates. Hence, consideration of overall dry scrubbing system performance demonstrates the total capability of the process to attain SO_2 removals in the range of commercial interest, 70 to 90 percent.

The values for overall SO_2 removal obviously are higher than the corresponding values for SO_2 removal in the spray dryer alone (Figure 5-37) reflecting the important contribution of the fabric filter to dry flue gas desulfurization. For example, at $\Delta T_{AS/SD} = 30^{\circ}F$ and $\Delta T_{SD} = 180^{\circ}F$, SO_2 removal values across the spray dryer range from 53 to 73 percent (Figure 5-12), while overall SO_2 removal levels vary from 70 to 94 percent (Figure 5-37). The trends of the curves for overall SO_2 removal in Figure 5-37 are very similar to the those for spray dryer SO_2 removal in Figure 5-12. The temperature trends also are similar and data scatter is comparable.

In considering the capability of the process to satisfy NSPS, the overall effects of the entire system must be evaluated. While the individual parameters that govern the performance of each unit can be controlled separately, there is an interrelationship between the two unit operations. Viewing the process as one overall system provides additional insight to the information garnered from the study of the two individual units in series.

Reproducibility

The results of reproducibility studies conducted on the spray dryer/fabric filter pilot plant system are presented for two different sets of cases in Tables 5.11 and 5.12. Each lists the results of four similar, non-consecutive test runs operating in a recycle mode. The runs from the 400 series were conducted in July 1980, while the runs from the 600 series were conducted in September 1980. The control variables are the spray dryer temperatures ($T_{IN/SD}$, $T_{OUT/SD}$, ΔT_{SD}, $\Delta T_{AS/SD}$), inlet SO_2 concentration (SO_2-IN), stoichiometric ratio (SR), recycle ratio (RR), spray dryer residence time (θ_R), and fabric filter air-to-cloth ratio (A/C).

In general, there was no difficulty in maintaining the targeted levels of the control variables. The relative variances are typically under 5 percent and almost always less than 10 percent. The lone exception is attributable to a single low value for recycle ratio in run 405R-2 in Table 5.11. (The relative variance, or coefficient of variation, is defined as the ratio of the

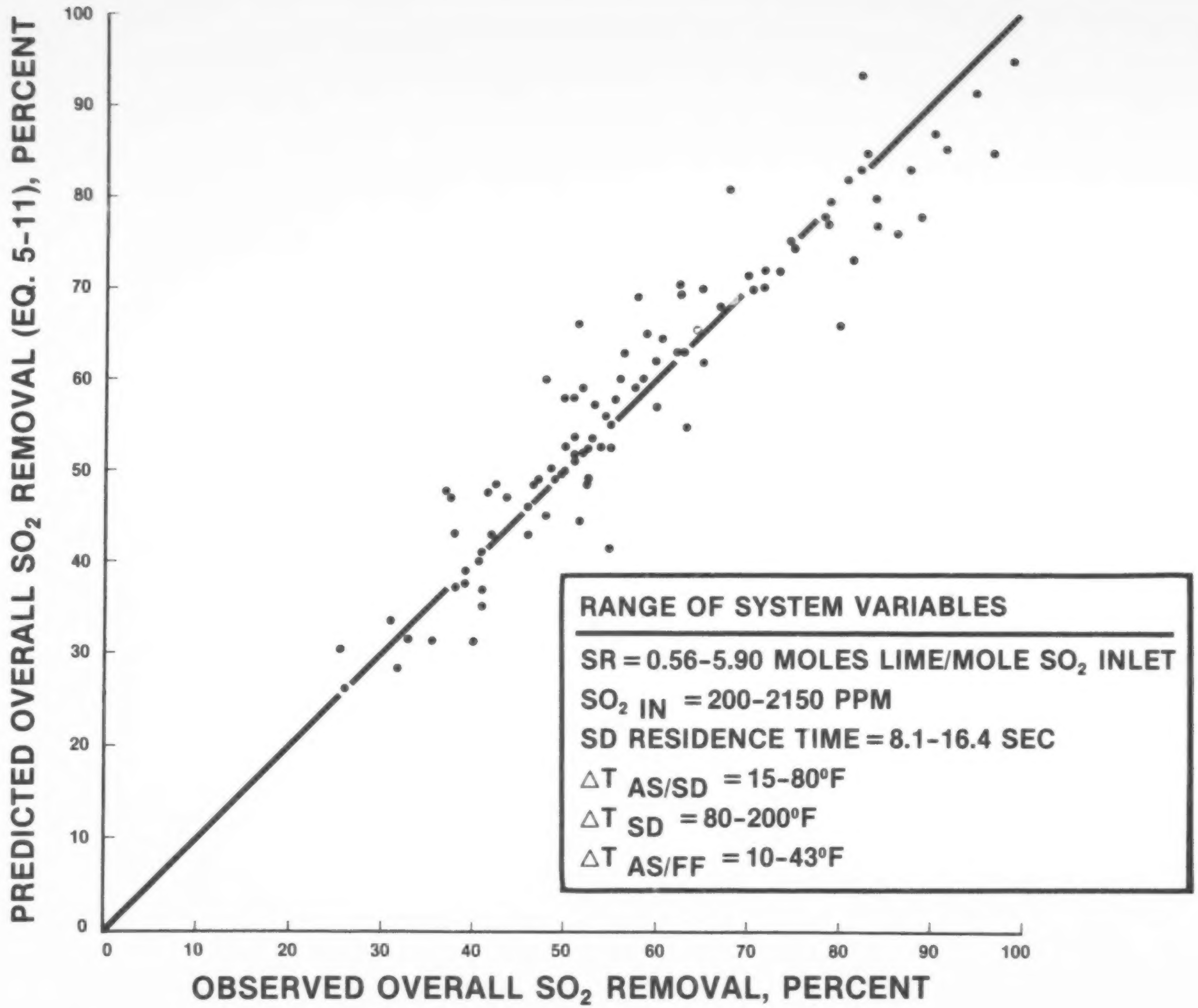


Figure 5-35. Parity Plot of Observed and Predicted Overall SO_2 Removal - Lime-Only Operation.

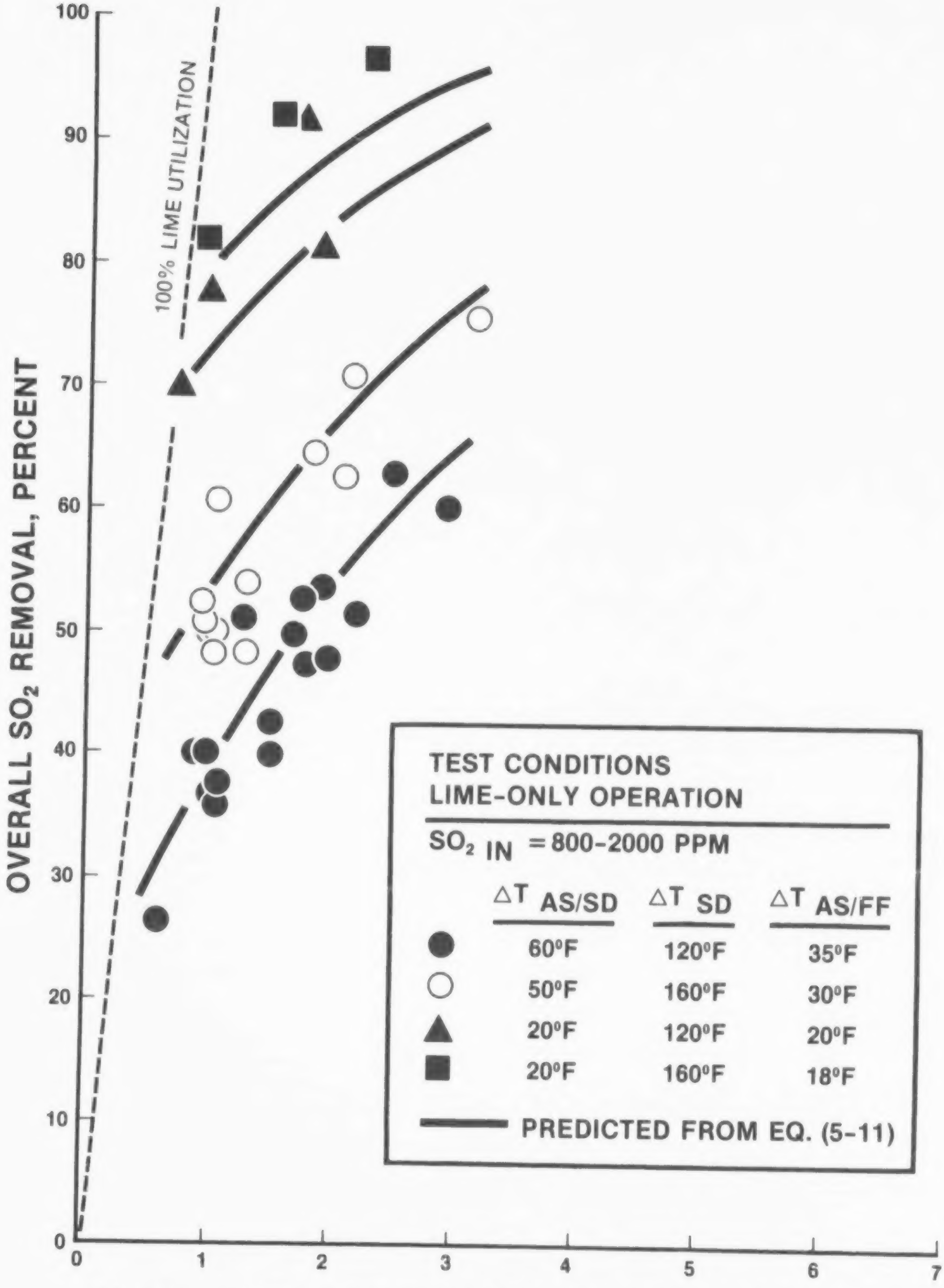


Figure 5-36. Comparison of Observed and Predicted Overall SO_2 Removal - Lime-Only Operation.

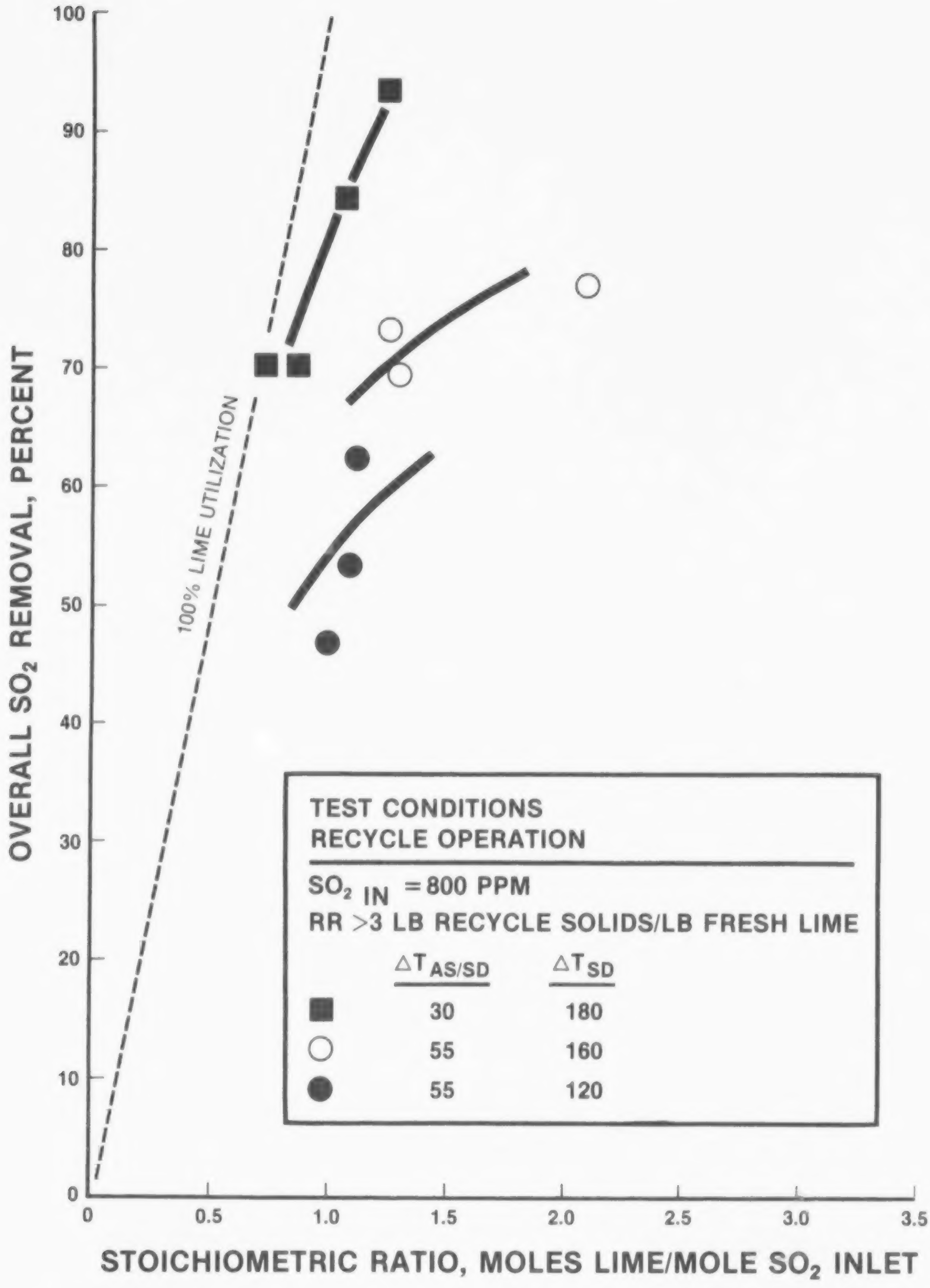


Figure 5-37. Overall SO_2 Removal - Recycle Operation.

standard deviation to the mean multiplied by 100.) For the two cases studied there is generally less variation in the spray dryer parameters than in the fabric filter parameters.

The variations in the SO_2 removal shown in Tables 5.11 and 5.12 provide good illustrations of the interrelationship between the spray dryer and fabric filter for SO_2 removal. In each case, the standard deviation of the overall SO_2 removal lies between that for spray dryer SO_2 removal and that for fabric filter SO_2 removal. For example in Case I (Table 5.11), the standard error associated with overall SO_2 removal is 3.3 percent, although the corresponding values for the spray dryer and fabric filter are 2.7 percent and 4.2 percent, respectively. In other words, the pilot plant system appears to be self compensating when a deviation occurs. From the data analysis, a deviation producing a lower than expected SO_2 removal in the spray dryer tends to result in higher than expected SO_2 removal in the fabric filter. The reverse situation also appears to be true. The compensating effect dampens the overall system performance variability and, in these cases, the reproducibility of overall SO_2 removal tends to be better than that expected based on individual unit values.

TABLE 5.11 PILOT PLANT SYSTEM REPRODUCIBILITY

Case I

Run No.	405	405R-1	405R-2	405 (800)	Mean	Standard Deviation
$T_{IN/SD}$, °F	339	339	340	337	339	1.3
$T_{OUT/SD}$, °F	187	186	180	178	183	4.4
ΔT_{SD}, °F	152	153	160	159	156	4.1
$\Delta T_{AS/SD}$, °F	58	59	50	49	54	5.2
$T_{IN/FF}$, °F	177	180	177	172	177	3.3
$T_{OUT/FF}$, °F	162	147	152	149	153	6.7
$\Delta T_{AS/FF}$, °F	38	23	28	24	28	6.8
SO_2-IN, ppmv	800	850	760	740	788	49
SO_2-MID, ppmv	365	400	320	310	349	42
$\Theta_{R/SD}$, sec	10.3	10.4	10.2	10.0	10.2	0.2
A/C_{FF}, fpm	2.08	2.08	2.13	2.17	2.12	0.04
SR, moles lime/ mole SO_2	0.91	0.99	1.07	1.08	1.01	0.08
Recycle Ratio, lb solids/ lb lime	3.10	3.00	2.27	3.14	2.88	0.41
Spray Dryer SO_2 Removal, %	50.7	48.4	53.9	54.1	51.8	2.7
Fabric Filter SO_2 Removal, %	9.9	15.8	11.8	19.3	14.2	4.2
Overall SO_2 Removal, %	55.6	56.5	59.3	63.0	58.6	3.3

TABLE 5.12 PILOT PLANT SYSTEM REPRODUCIBILITY

Case II

Run No.	605	611	617	623	Mean	Standard Deviation
$T_{IN/SD}$, °F	304	305	302	295	302	4.5
$T_{OUT/SD}$, °F	181	185	184	177	182	3.6
ΔT_{SD}, °F	123	120	118	118	120	2.4
$\Delta T_{AS/SD}$, °F	56	60	61	54	58	3.3
$T_{IN/FF}$, °F	177	183	180	173	178	4.3
$T_{OUT/FF}$, °F	147	155	155	160	154	5.4
$\Delta T_{AS/FF}$, °F	26	34	36	42	35	6.6
SO_2-IN, ppmv	700	750	770	750	743	30
SO_2-MID, ppmv	350	500	435	430	429	61
$\theta_{R/SD}$, sec	10.3	9.5	9.8	10.2	10.0	0.4
A/C_{FF}, fpm	2.11	2.30	2.22	2.12	2.19	0.09
SR, moles lime/ mole SO_2	1.17	1.08	1.08	1.11	1.11	0.04
Recycle Ratio, lb solids/ lb lime	3.03	3.04	2.98	2.95	3.00	0.04
Spray Dryer SO_2 Removal, %	47.1	26.6	38.1	38.8	37.7	8.4
Fabric Filter SO_2 Removal, %	13.1	20.5	21.2	16.4	17.8	3.8
Overall SO_2 Removal, %	54.1	41.6	51.2	48.9	49.0	5.3

SECTION 6

SPRAY DRYER ATOMIZER VARIABLES

PILOT TEST RESULTS

The pilot plant spray dryer is equipped with a rotary spinning disc atomizer to produce slurry droplets to capture SO_2 from the flue gas. The rate of reaction between SO_2 in the gas phase and lime in the slurry droplet is directly affected by the gas-slurry interfacial surface area, or slurry droplet size. The reaction between lime and SO_2 occurs in the liquid phase. Since SO_2 must be transported from the flue gas and solid lime must be dissolved into the liquid phase, the reaction will occur at a good rate as long as the droplet remains wet enough.

The SO_2 removal reaction competes against evaporation which removes water from the slurry droplet. If the initial size of the slurry droplet is too small, it will dry too quickly and limit the extent of reaction. If the initial slurry droplet is too large, the reaction proceeds favorably but drying is not complete, resulting in wet product solids which are difficult to handle. As with spray dryer outlet temperature, a balance must be struck on droplet size. The optimum initial slurry droplet size is that which permits maximum SO_2 removal while still yielding a manageably dry solids product.

Because of the complexities involved, it is important to carefully investigate the effects of the spray dryer atomizer variables. Slurry droplet size was not measured directly, but its effects on SO_2 removal were investigated using the atomizer operating parameters as independent correlating variables. During August 1980, a series of tests was conducted to study the effect of the following spray dryer atomizer variables on SO_2 removal:

- Atomizer Disc Speed
- Wheel Type
- Gas Vane Type.

Atomizer Disc Speed

Lime-Only

In order to examine the effect of atomizer speed on SO_2 removal, three different speeds, 10,600, 12,360 and 13,920 rpm, were investigated. The data gathered from these runs are tabulated in Table 6.1. According to Figure 6-1, somewhat greater SO_2 removal is obtained at an atomizer speed of 10,600 rpm than at higher atomizer speeds (12,360 and 13,920 rpm). However, the moisture content of the solids collected in tests at 10,600 rpm is considerably higher than that of solids produced at either 12,360 rpm or 13,920 rpm (Figure 6-2).

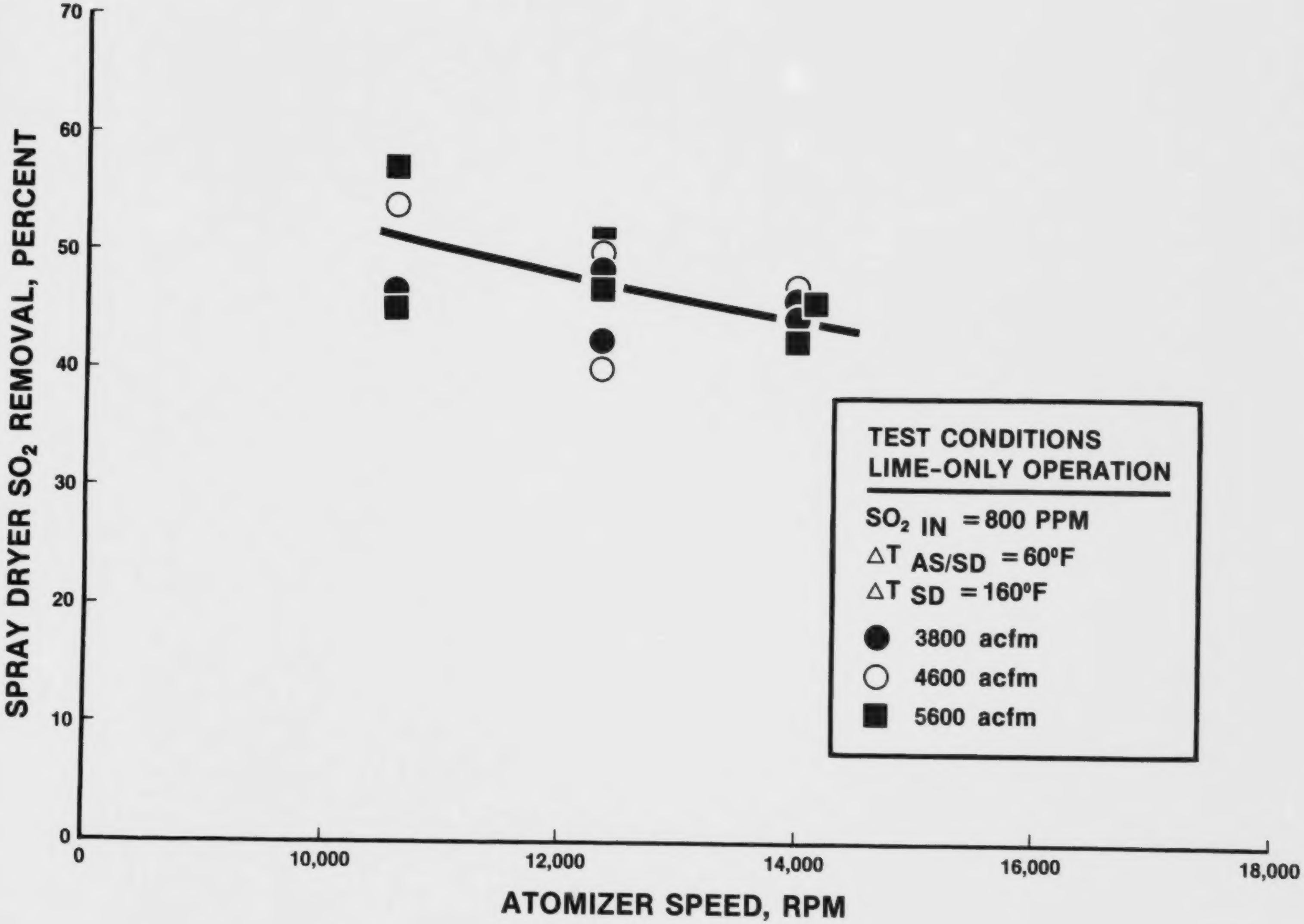


Figure 6-1. Effect of Atomizer Speed on Spray Dryer SO_2 Removal.

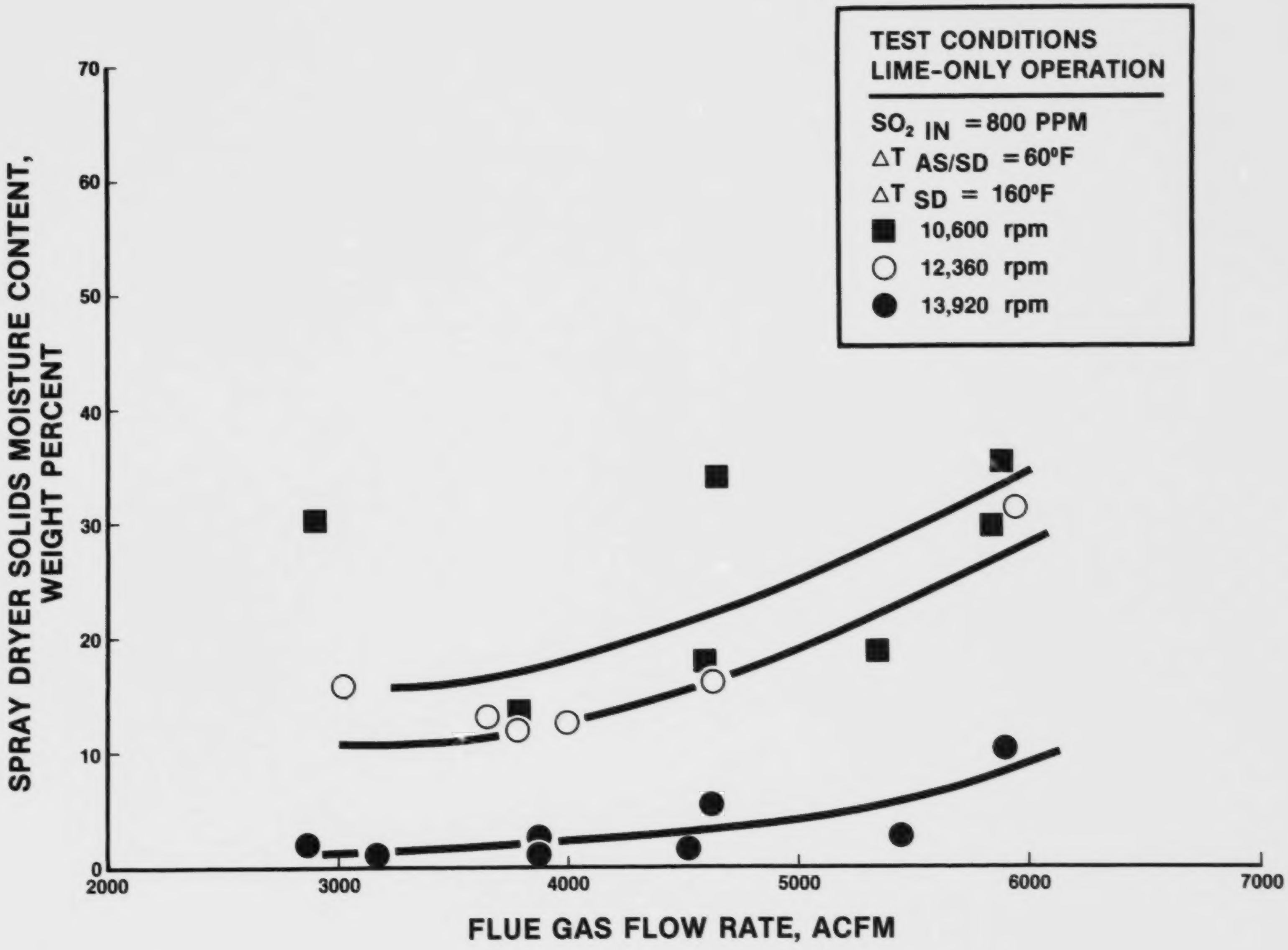


Figure 6-2. Effect of Flue Gas Flow Rate and Atomizer Speed On Spray Dryer Solids Moisture Content.

While SO_2 removal at the 10,600 rpm atomizer speed is higher, the moisture content of the FGD solids/fly ash mixture collected at this condition is too great for practical operation.

TABLE 6.1 EFFECT OF ATOMIZER SPEED ON SPRAY DRYER SO_2 REMOVAL

Run No.	Atomizer Speed (rpm)	Stoichiometric Ratio (Moles Lime/ Mole SO_2 inlet)	Spray Dryer Temperature T_{IN} (°F)	Spray Dryer Temperature T_{OUT} (°F)	Spray Dryer Gas Flow (acfm)	Spray Dryer SO_2 Removal (%)
501R	13,920	1.04	341	190	4635	46.8
502	13,920	1.19	341	182	5900	45.1
503R	13,920	1.14	350	188	5460	42.4
504	13,920	0.96	342	182	3825	45.7
504R	13,920	1.00	336	175	3825	43.9
507	12,360	0.98	342	180	5950	46.7
508	12,360	0.99	342	182	4630	49.8
508R	12,360	1.04	342	182	4610	40.6
509	12,360	1.00	342	182	3775	42.4
523	12,360	1.09	337	179	5065	51.4
524	12,360	0.98	340	178	3980	48.2
511	10,600	1.11	346	186	5860	45.5
512	10,600	1.09	343	184	4580	53.8
512R	10,600	1.05	338	177	5560	56.9
513	10,600	1.14	341	181	3865	46.6
514	10,600	1.07	311	153	2915	61.7

The rotary disc atomizer used in the pilot tests is 7 3/8 in. diameter and consists of a titanium body with six silicon carbide ports inserted around the periphery. The bottom plate of the titanium disc is coated with aluminum oxide for protection against slurry abrasion.

Recycle

A limited number of tests was conducted using a wheel speed of 10,600 rpm while operating in the recycle mode. Figure 6-3 indicates that SO_2 removal across the spray dryer is similar or, perhaps slightly higher, at 10,600 rpm than at 13,920 rpm. Lowering the wheel speed from 13,920 rpm to 10,600 rpm produces larger initial slurry droplets, which in turn tends to increase SO_2 removal, but also results in more moisture in the discharged solids. A lower rpm reduces the spray droplet surface area for SO_2 mass transfer but since the droplet remains wetter for a longer period of time, SO_2 removal is enhanced somewhat.

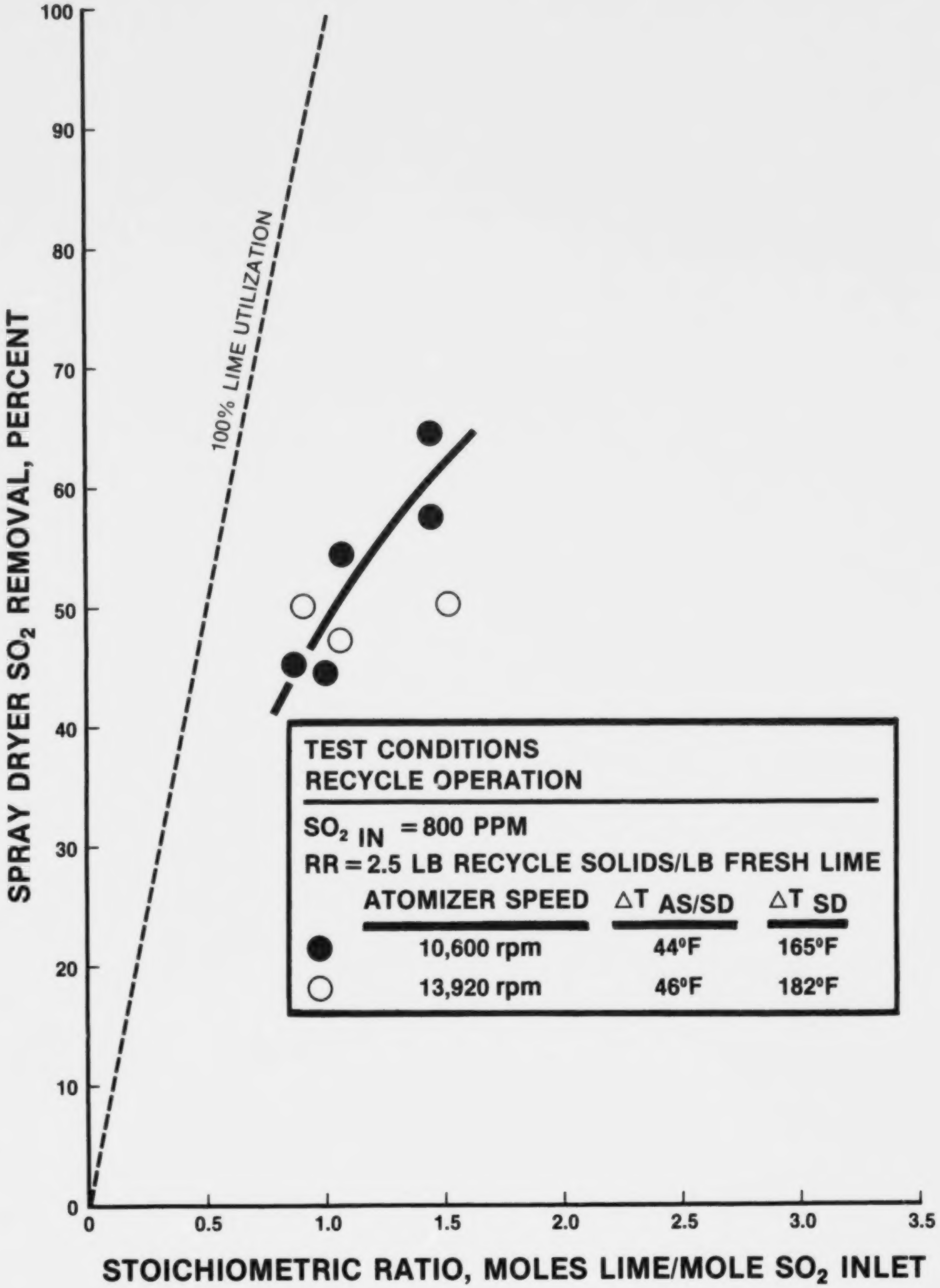


Figure 6-3. Effect of Atomizer Speed on Spray Dryer SO_2 Removal.

The effect of approach to adiabatic saturation temperature on SO_2 removal was also investigated at an atomizer speed of 10,600 rpm. Figure 6-4 shows the pronounced effect of approach to adiabatic saturation on SO_2 removal. Decreasing ΔT_{AS} from 60° to 40°F increases SO_2 removal from 41 percent to 53 percent.

Moisture Content

Atomizer speed has a direct effect on the SO_2 removal and on the moisture in the solid materials discharged from the spray dryer. Operation at low atomizer speed creates large slurry droplets which, due to high moisture content, somewhat enhances SO_2 removal but also often produces high moisture content solids that are difficult to discharge from the spray dryer hopper. High speed atomization, on the other hand, produces finer droplets which dry very rapidly. Because of their reduced moisture content, produced at similar operating conditions, the smaller droplets do not as effectively absorb SO_2 from the flue gas resulting in lower SO_2 removal.

Figure 6-5 shows that at the higher atomizer speeds the fraction of total solids collected in the spray dryer decreases. Atomizer speed directly affects the initial droplet size for a given atomizer wheel. Higher speed initially generates finer droplets from the atomizer which tends to result in smaller solid particles upon drying. As a consequence, a smaller fraction of the total solids is collected in the spray dryer (Figure 6-5).

The moisture content of the spray dryer solids increases rapidly as the spray dryer operating temperature approaches the adiabatic saturation temperature. Figure 5-8 illustrates the effect of approach to adiabatic saturation temperature on the moisture content of the spray dryer solids. Operation nearer the adiabatic saturation temperature results in a reduced rate of water evaporation from the slurry droplets and produces higher moisture content product. Empirically, it was found in the pilot tests that a solids moisture content in the 15-20 wt.% range is the upper limit for satisfactory, long-term solids handling and discharge. If the moisture content exceeds this range, the solids collected tend to be sticky and cling to the internals of the discharge hoppers. Hopper bridging and discharge valve plugging result.

Figure 6-6 shows that increased spray dryer flue gas residence time reduces the moisture content of the solids collected from the spray dryer. However, the effect of atomizer speed on solids moisture content is considerably greater than that of gas residence time.

Based on the pilot test results, spray dryer solids contain more moisture (10-25 wt.%) than do fabric filter solids (<5 wt.%). Additional solids drying occurs between the time the flue gas leaves the spray dryer and particulate from the stream is collected in the fabric filter hopper. It is likely that the additional drying causes some agglomerates to disintegrate and contributes to the collection of finer particulates in the fabric filter.

Wheel Type

Use of an atomizer wheel containing six silicon carbide, 5/16 in. diameter ports produced enhanced SO_2 removal in the spray dryer over that obtained with

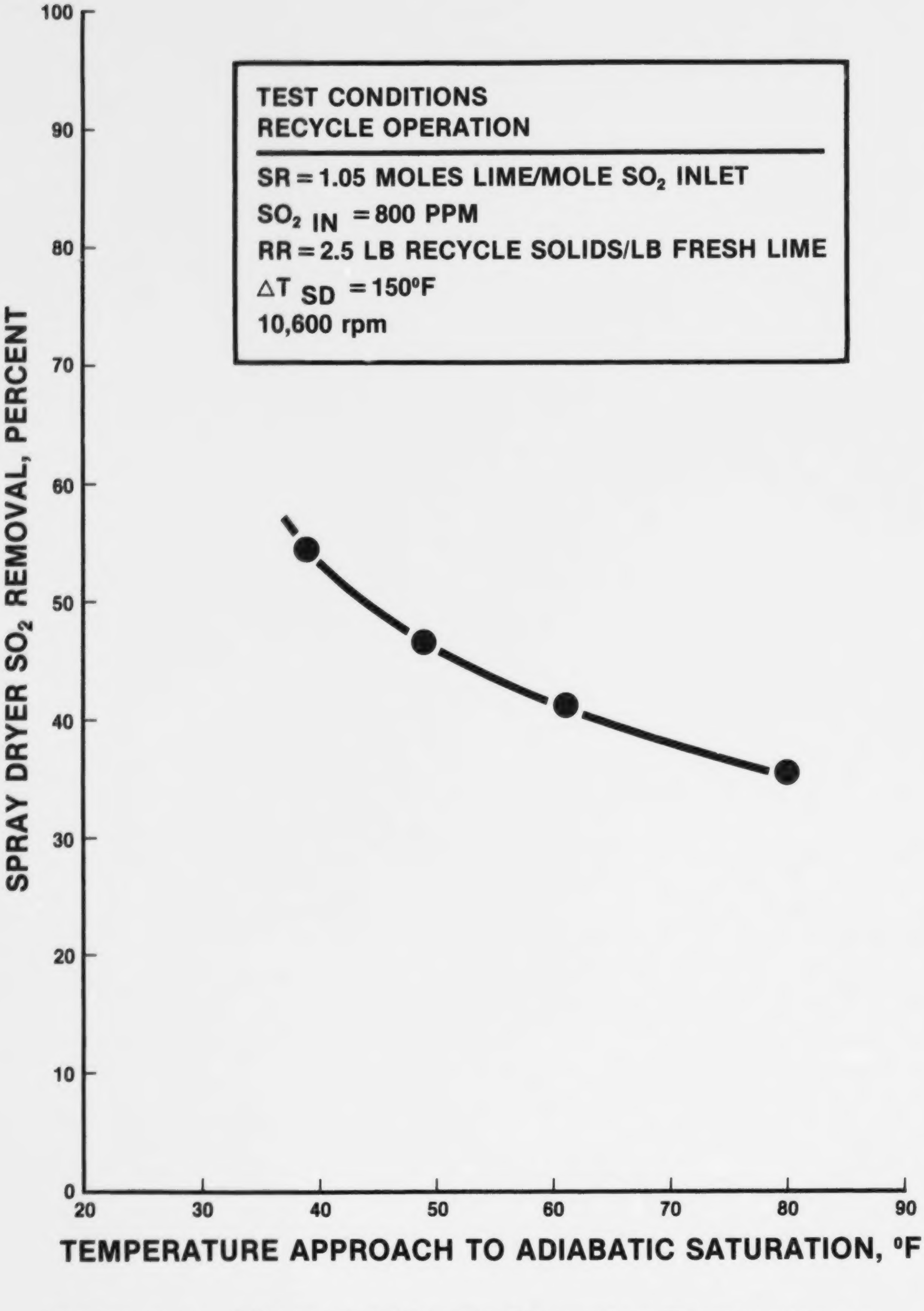


Figure 6-4. **Effect of Adiabatic Saturation Temperature on Spray Dryer SO_2 Removal.**

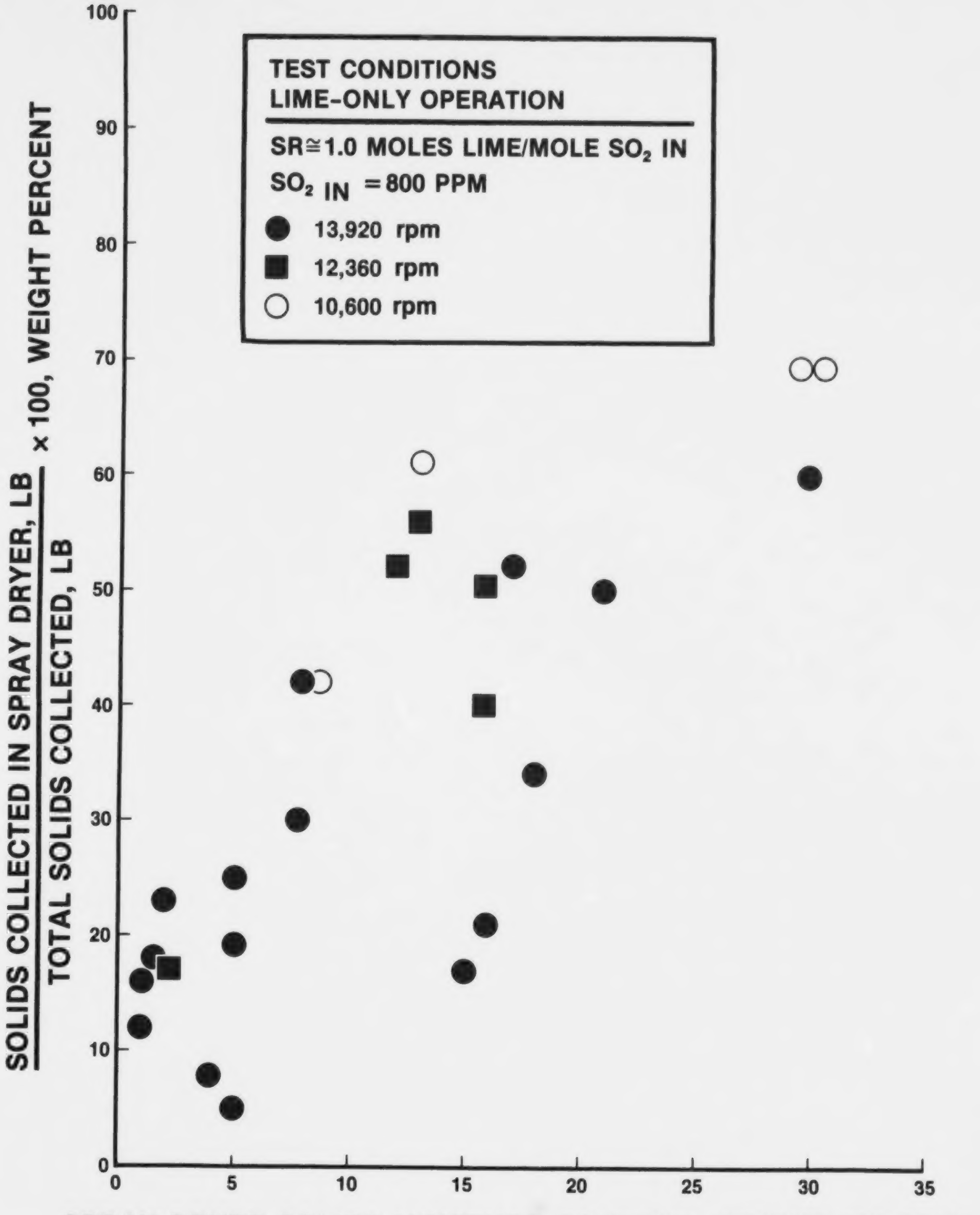


Figure 6-5. Solids Collection in Spray Dryer Relative to Total Solids Collection.

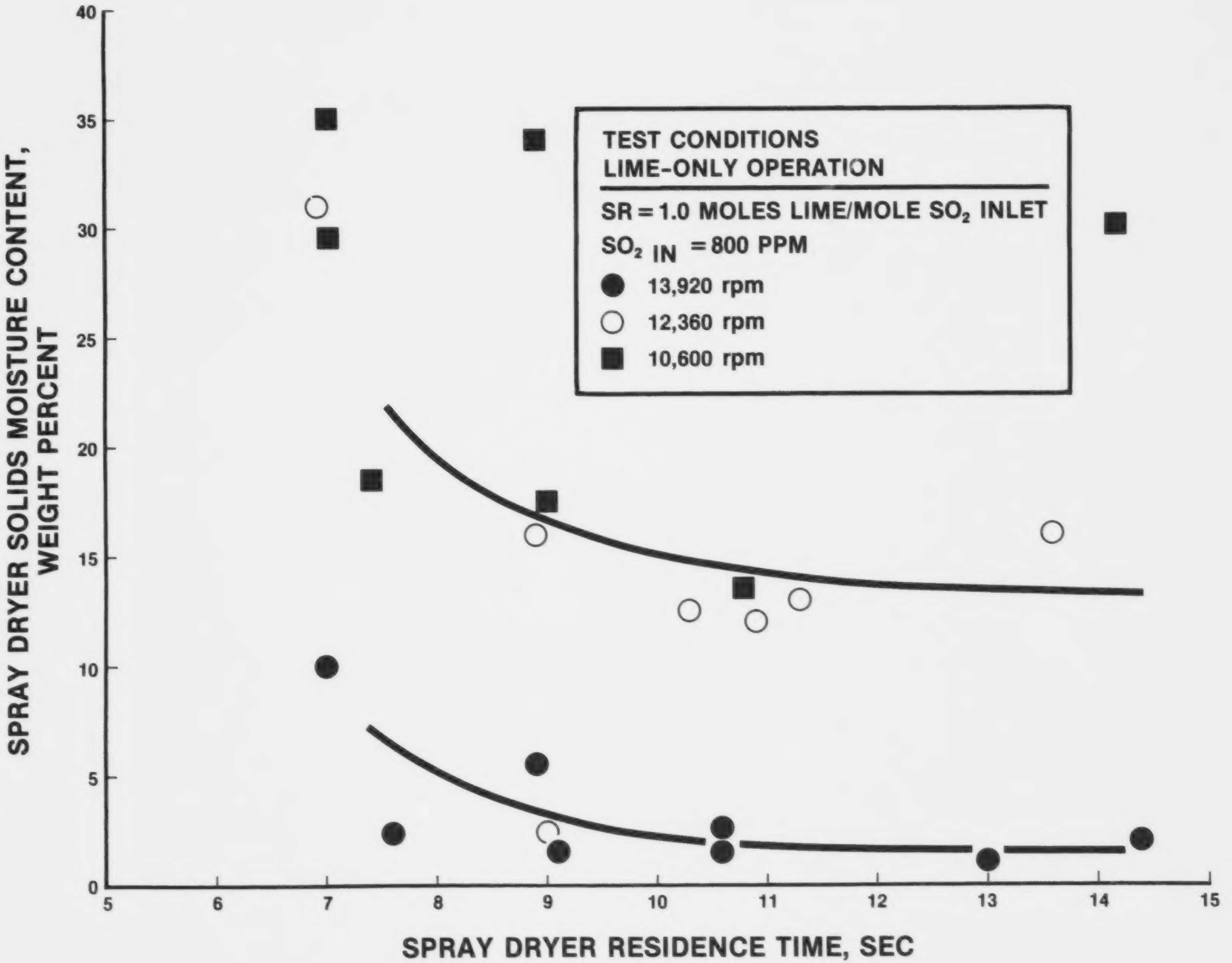


Figure 6-6. Effect of Residence Time on Spray Dryer Solids Moisture Content.

a stainless steel disc containing approximately 80 1/8-in. wide slots on its periphery at the same atomizer speed (13,920 rpm) (Figure 6-7).

Gas Vane Type

No significant difference in SO_2 removal was observed between two types of flue gas distribution vanes tested (Figure 6-8). The flue gas vanes have an outside diameter of 30 in. and inside diameter of 9 in. Each vane contains 36 blades equally spaced 10° apart. One type of vane produces gas flow co-rotational to the atomizer slurry droplet flow and has blades at a 30° angle off the vertical axis. The other gas vane generates flow counter-rotational to the atomized slurry and has blades at a 60° angle off the vertical axis.

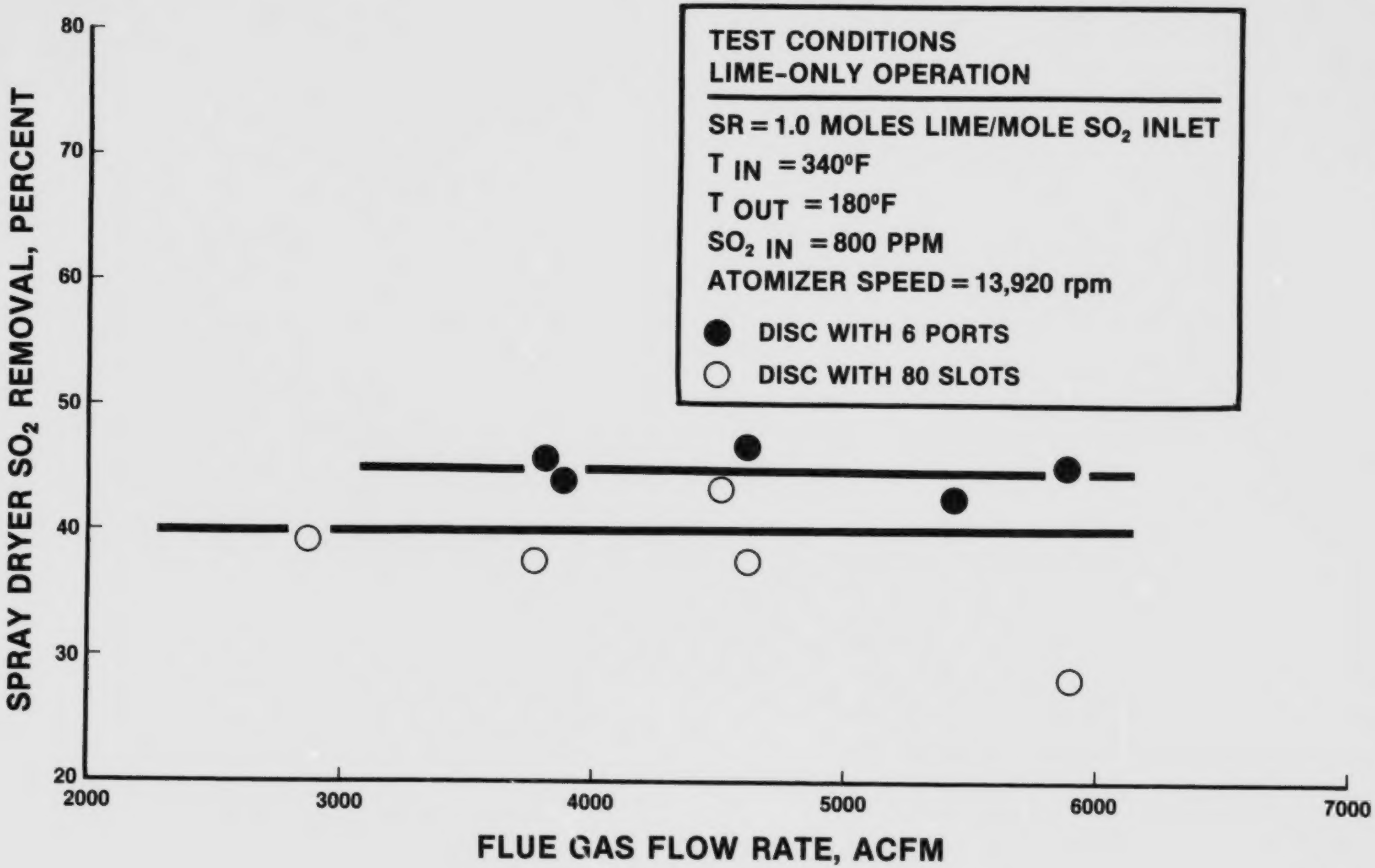


Figure 6-7. Effect of Wheel Type on Spray Dryer SO_2 Removal.

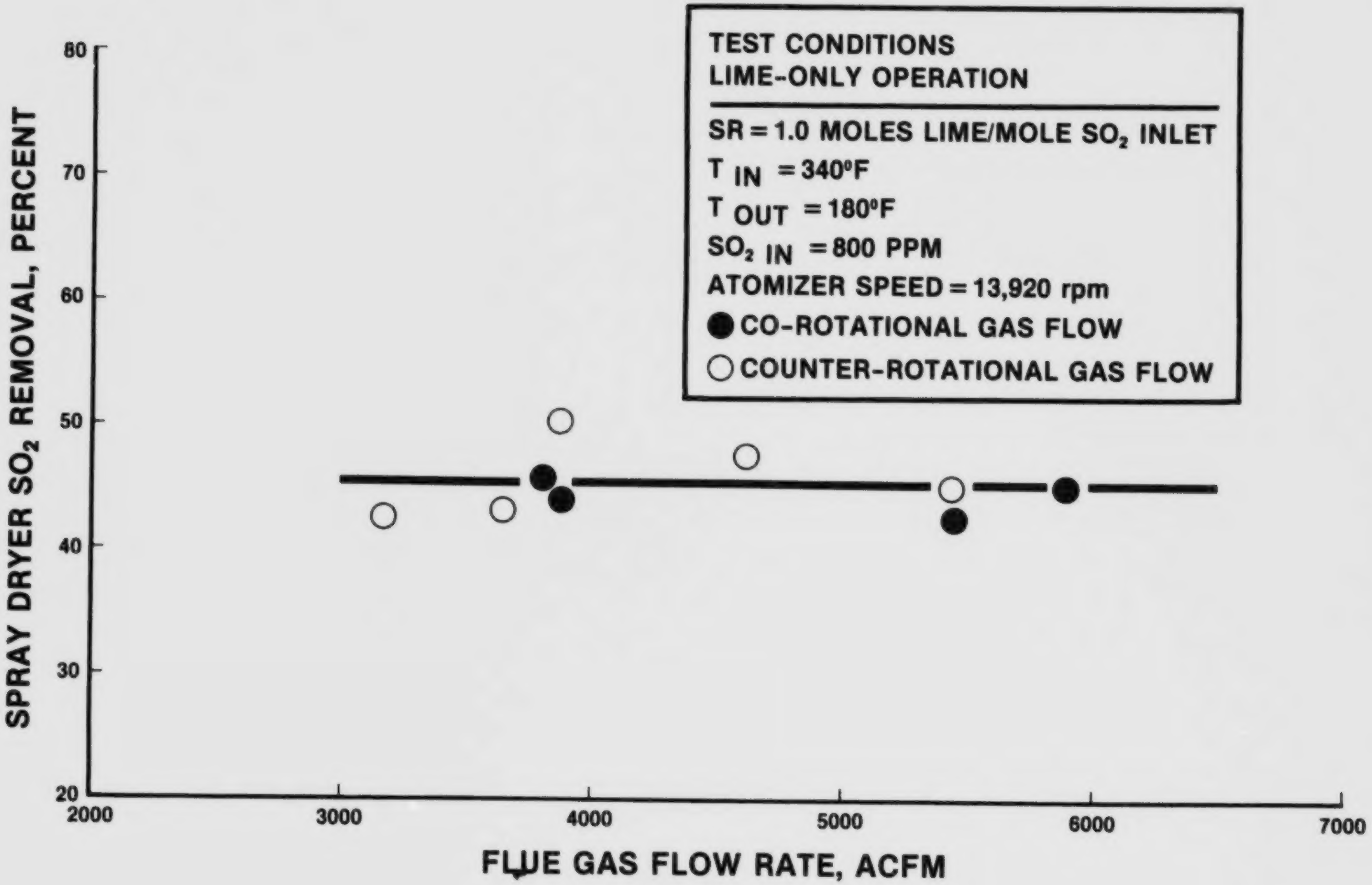


Figure 6-8. Effect of Gas Vane Type on Spray Dryer SO_2 Removal.

SECTION 7

LIME SLAKING

PILOT TEST RESULTS

In addition to the importance of slurry droplet size on SO_2 removal, the formation of finely divided lime particles produced by operating at proper slaking conditions is important for effective SO_2 removal in the spray dryer. A number of variables have been observed to have an important effect on slaked lime quality. For the present investigation, four variables were studied for their effect on SO_2 removal.

- Slaking Temperature
- Slaking Water Quality
- Lime Source
- Slaker Paddle Speed

Slaking Temperature

In order to examine the effect of slaking temperature on SO_2 removal, a series of runs was conducted with different lime slaking temperatures: 160, 175, 190°F. Spray dryer SO_2 removal experienced using the lime slaked at 175°F is slightly lower than that for limes slaked at 160° and 190°F (Figure 7-1). Samples of Ash Grove lime slaked at each temperature were analyzed for particle size distribution via a light scattering method (Quantimet). Plots of particle size distribution for these slaked limes show considerable similarity, but the average particle diameter for lime slaked at 160°F is slightly smaller than for those slaked at 175°F and 190°F (Figure 7-2). While no reason is obvious for the modest variation in SO_2 removal with slaking temperature, it does not appear that the particle size of slaked lime is a contributing factor in these tests.

Slaking Water Quality

To determine the effect of slaking water quality on spray dryer SO_2 removal, three different types of water were used to slake Ash Grove lime:

- Normal tap water available at Comanche
- Tap water doped with 1260 ppm sulfate ion
- Boiler blowdown water.

For the majority of the test program, normal process water from Comanche Station was used for lime slaking. Five runs were conducted in which the lime was slaked with boiler blowdown water (Runs 821-825). Five additional runs

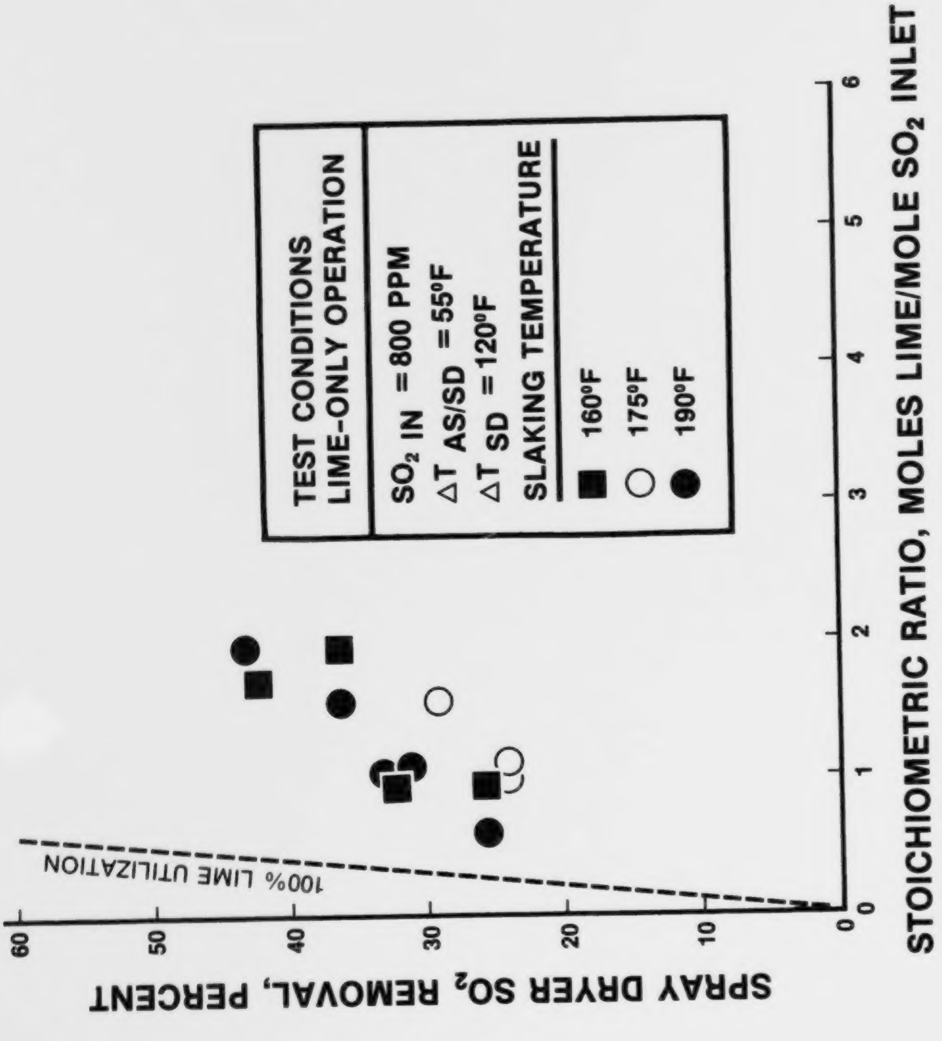


Figure 7-1. Effect of Lime Slaking Temperature on Spray Dryer SO_2 Removal.

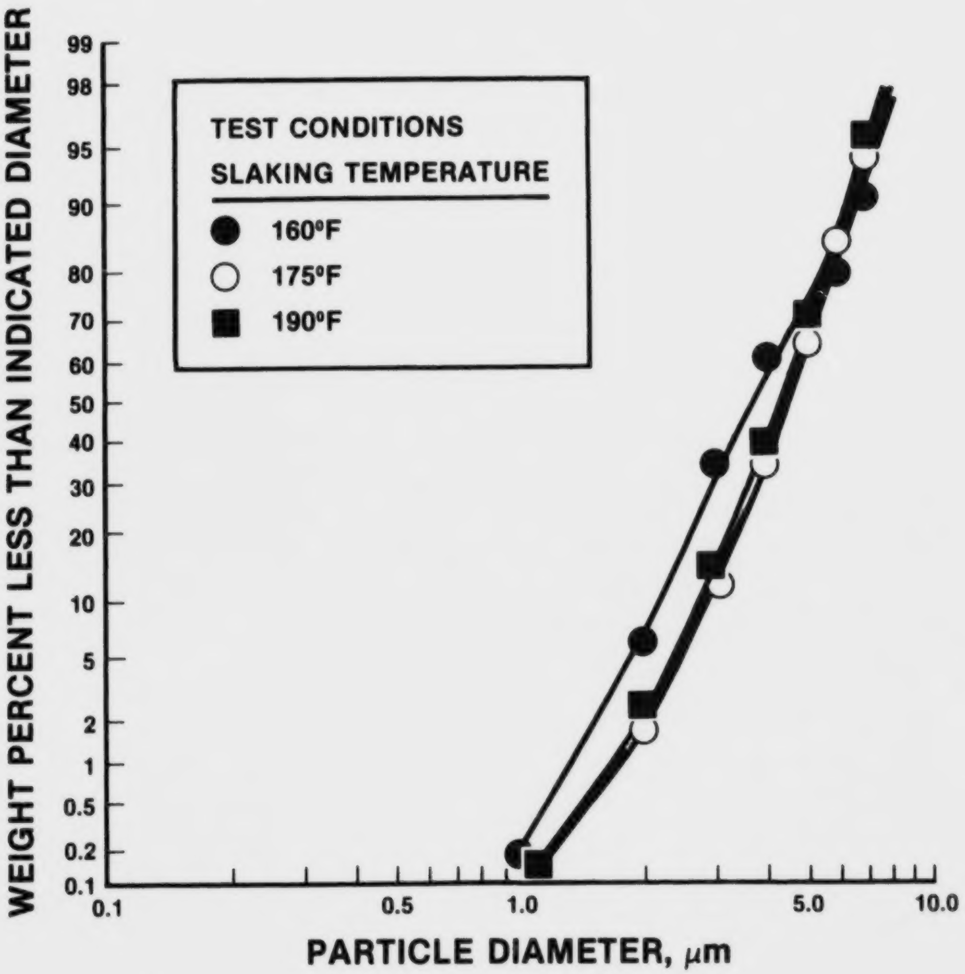


Figure 7-2. Effect of Lime Slaking Temperature on Particle Size Distribution.

were conducted in which the lime was slaked with sulfate-doped process water (Runs 816-820). The chemical composition of the various slaking waters is presented in Table 7.1. The analyses were performed at the Research-Cottrell analytical laboratory, and the analytical procedures used are included in Appendix C. For the runs testing different slaking waters, normal process water was used for dilution and for trim water to the spray dryer.

TABLE 7.1 SLAKING WATER CHEMICAL COMPOSITIONS

Specie	Normal Water (ppm)	Boiler Blowdown Water (ppm)	Sulfate-Doped Water (ppm)
$SO_3^=$	0	0	0
$SO_4^=$	226	133	1260
Cl^-	7	0	3
Ca^{++}	39	35	66
Mg^{++}	13	1	<1
Na^+	2	9	486
K^+	3	<1	3
Alkalinity as $CaCO_3$	98	118	176
TDS	292	200	1868
pH	7.9	8.8	11.5

As Figure 7-3 shows, no significant difference in spray dryer SO_2 removal was observed using the three different quality waters for lime slaking. Particle size distributions of lime slaked using the various types of water (Figure 7-4) indicate that considerably larger particles are produced when lime is slaked with high-sulfate water compared with either tap water or boiler blowdown water.

Lime Source

Limes from three different sources were compared for their effects on SO_2 removal in the spray dryer. These sources were:

- Peter Lien (South Dakota)
- Ash Grove (Missouri)
- Salida (Colorado)

Although almost all of the test program was conducted using Ash Grove

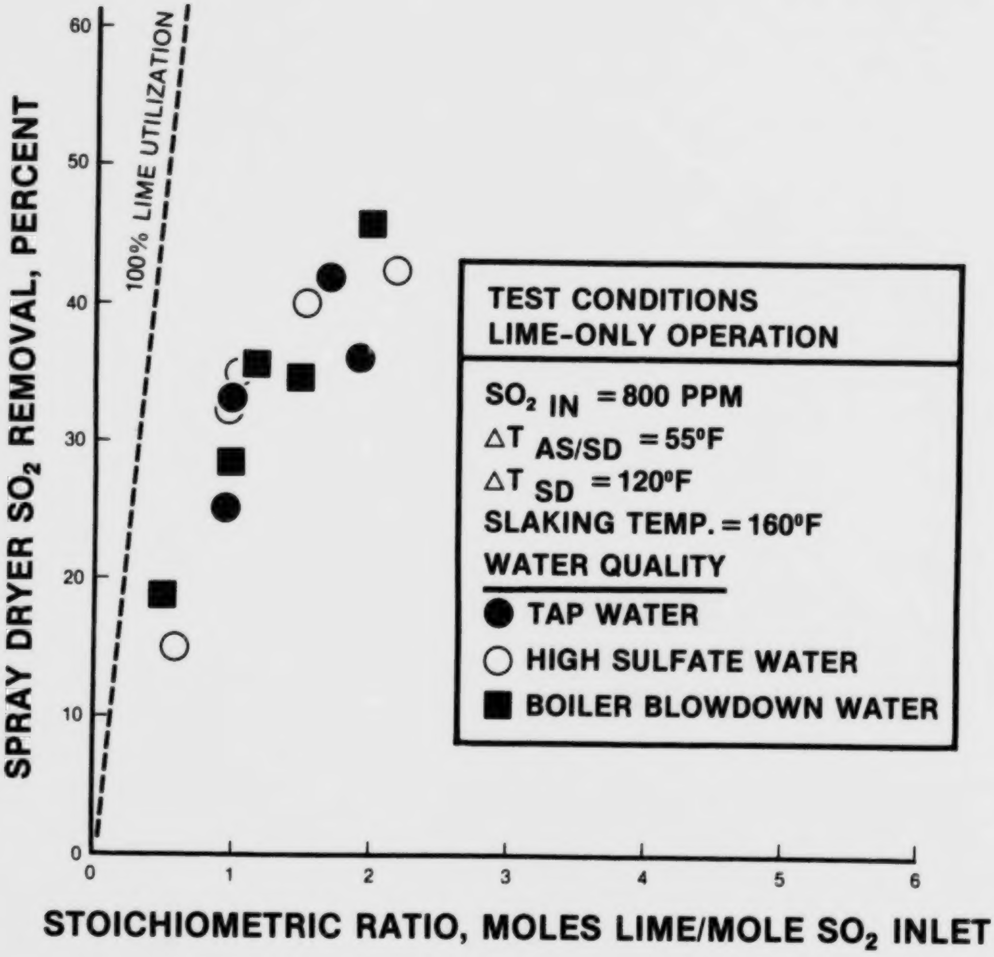


Figure 7-3. Effect of Lime Slaking Water Quality on Spray Dryer SO_2 Removal.

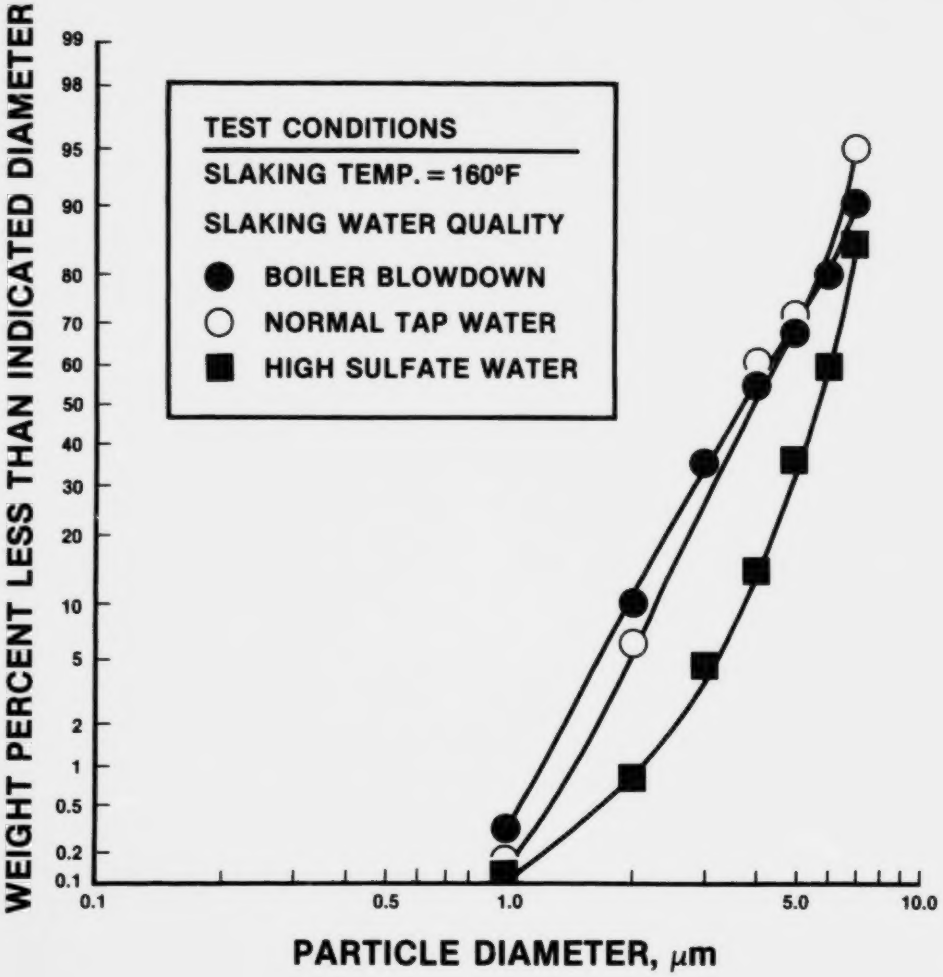


Figure 7-4. Effect of Slaking Water Quality on Lime Particle Size Distribution.

Calmax quicklime, five tests each were carried out using Peter Lien quicklime (Runs 826-830) and Salida quicklime (Runs 831-835). Table 7-2 presents comparative analyses of the three types of quicklime. These analyses were performed at the Research-Cottrell analytical labs. The analytical procedures are included in Appendix C.

TABLE 7.2 COMPARATIVE LIME ANALYSIS

Type of Lime	CaO (Wt.%)	MgO (Wt.%)	Na_2O (ppmw)	K_2O (ppmw)	Acid Insolubles (Wt.%)	AWWA Reactivity	$Ca(OH)_2$ by TGA (Wt.%)	Free Base (Wt.%)
Ash Grove	70.6	0.28	146	81	0.21	Low	69.92	79.7
Peter Lien	76.3	0.63	394	551	0.50	Low	24.68	88.9
Salida	76.8	3.61	77	116	0.79	Medium	28.28	78.8

Pilot tests conducted using the three limes slaked at 160°F showed no significant differences in SO_2 removal (Figure 7-5). SO_2 removal ranged to about 45 percent as the stoichiometry was varied as high as about 2.0 moles lime per mole SO_2 fed to the spray dryer. Other operating parameters were held constant in the comparison runs. Particle size distributions for the three slaked limes were quite similar (see Figure 7-6).

The ground lime was slaked in a pugmill slaker. The hydrated lime slurry was analyzed for $Ca(OH)_2$ content by titration with 1 N HCl to a phenolphthalein end point. The available lime content ($Ca(OH)_2$ content) of the hydrated slurry typically amounted to 97 percent of the total quicklime added. Hence, slaking of the quicklime was fairly complete. The available lime content ($Ca(OH)_2$ content) is used to calculate the stoichiometric ratios presented in this report.

Slaker Paddle Speed

The effect of the degree of agitation during lime slaking on SO_2 removal was investigated by operating at two different slaker paddle speeds, 43 and 93 rpm. As Figure 7-7 shows, slaking at a paddle speed of 43 rpm produced higher spray dryer SO_2 removal than slaking while operating at 93 rpm. Lower paddle speed results in a longer slaker residence time for the lime, which produces a greater degree of slaking. According to Figure 7-8, the particle size of Ash Grove lime slaked at 43 rpm averages somewhat less than that slaked at 93 rpm, which may contribute to the higher SO_2 removal observed.

Particle Size Distribution

Table 7.3 presents the mean particle diameter of lime samples slaked at several different conditions. As shown in Table 7.3, the lime is slaked to very fine particle sizes under almost all conditions with the mean particle diameter ranging from 3.5 to 4.4 μm. An exception occurred in the case where

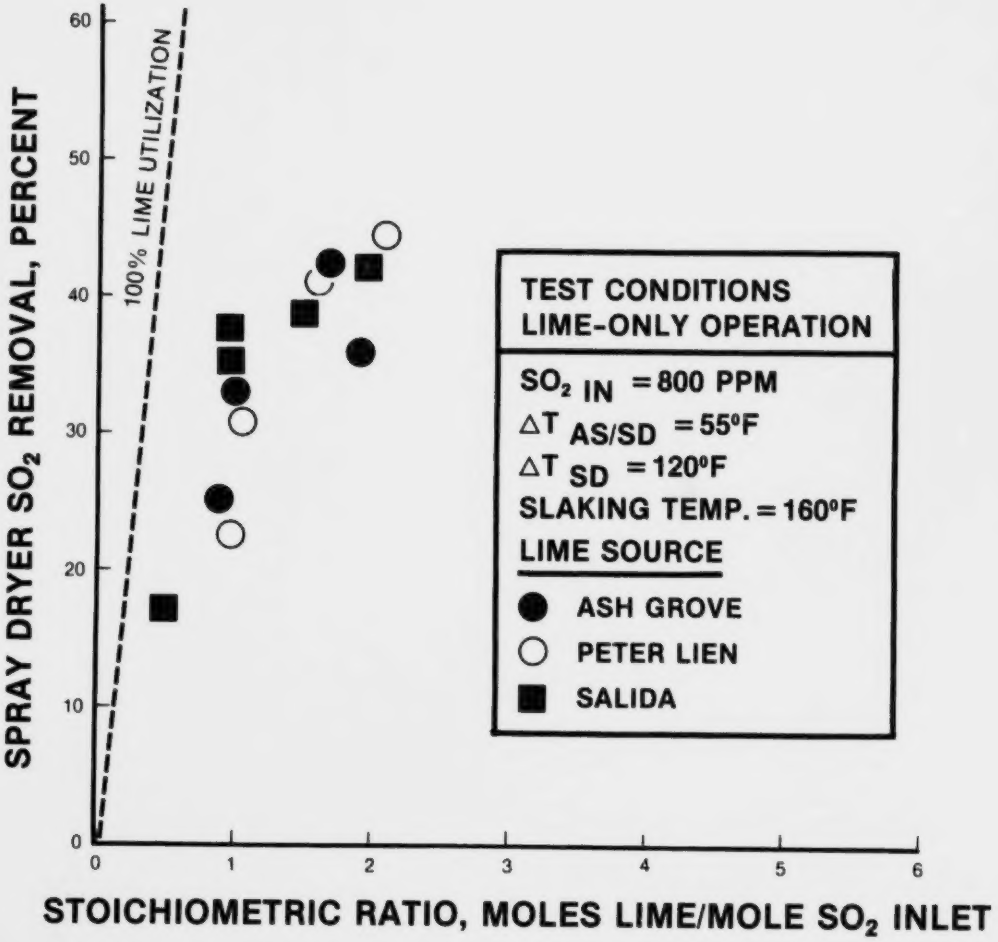


Figure 7-5. Effect of Lime Source on Spray Dryer SO_2 Removal.

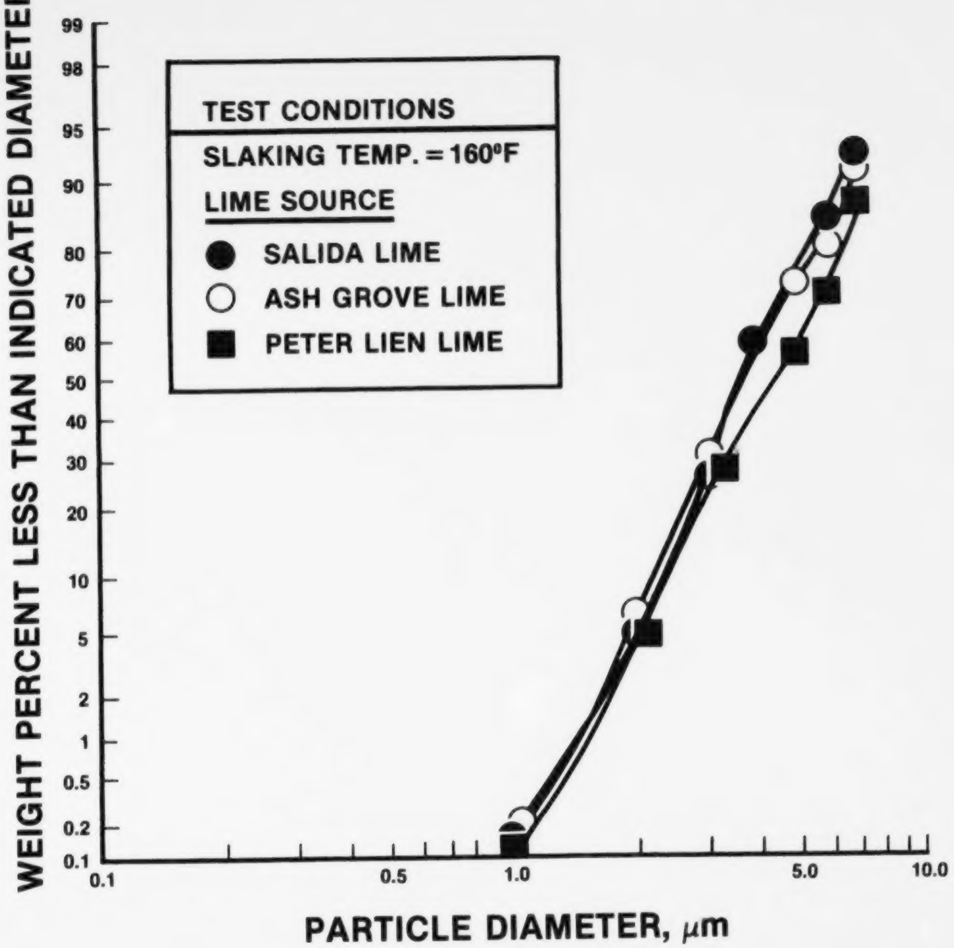


Figure 7-6. Effect of Lime Source on Particle Size Distribution.

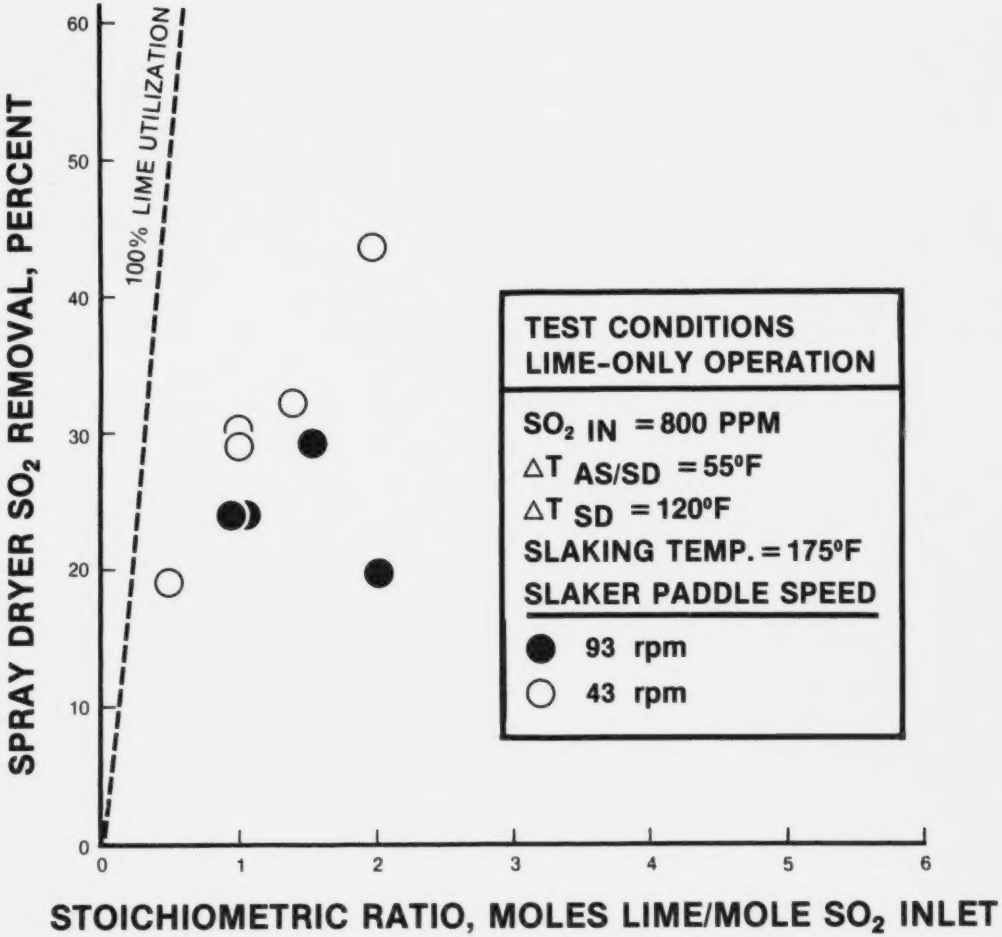


Figure 7-7. Effect of Lime Slaker Paddle Speed on Spray Dryer SO_2 Removal.

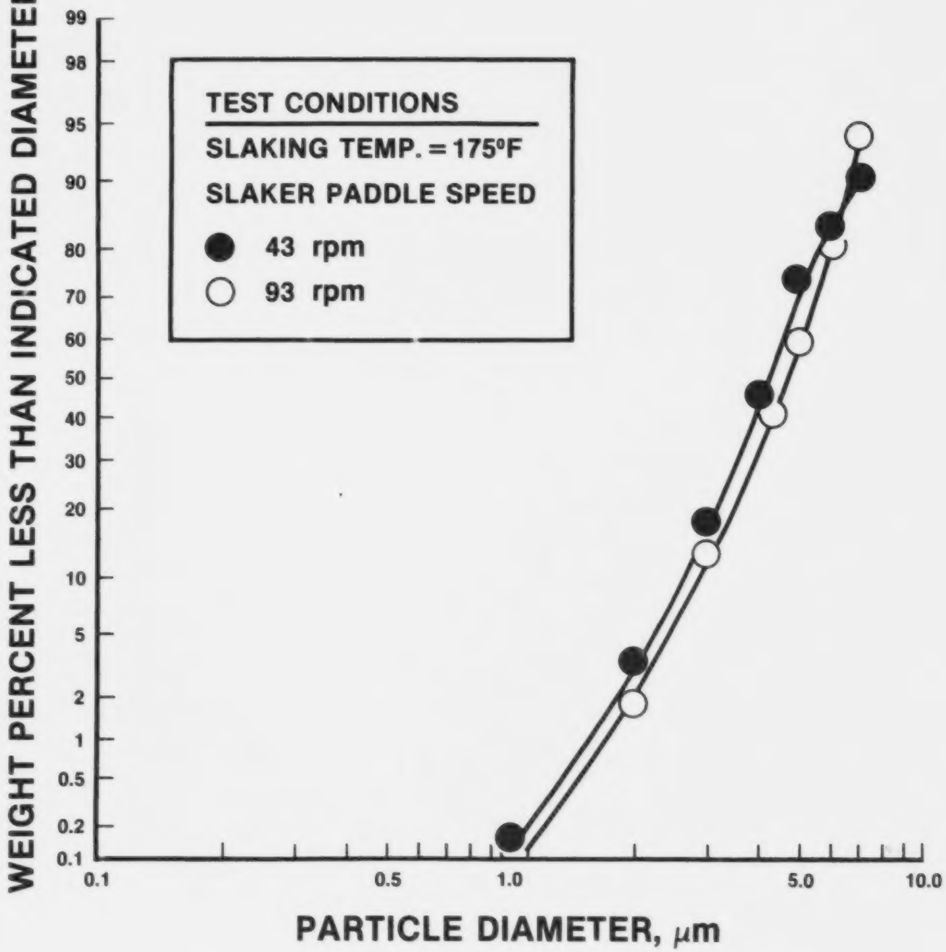


Figure 7-8. Effect of Slaker Paddle Speed on Lime Particle Size Distribution.

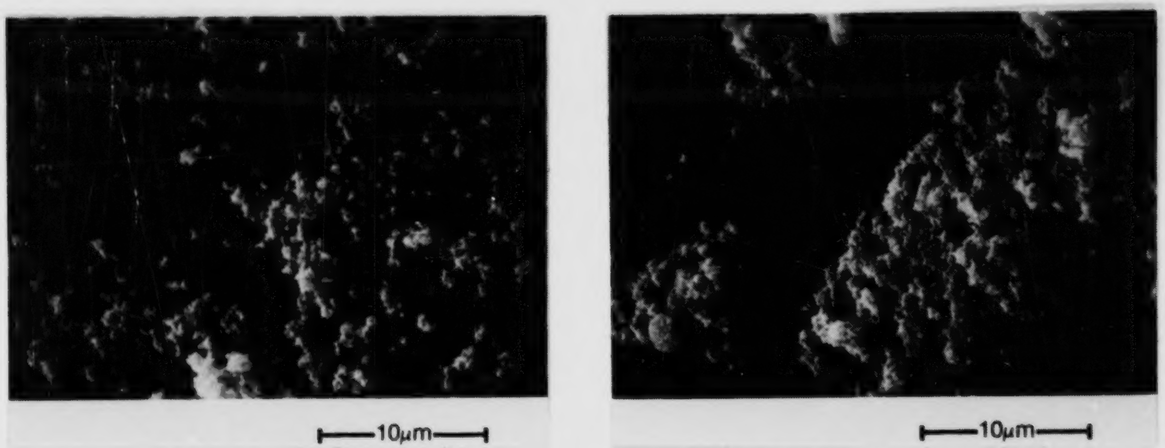
the slaking water contained a high concentration of sulfate ion (1260 ppm), which produced a larger average particle size. The mean particle diameter is 5.7 µm, but high sulfate content slaking water is known to produce poorly slaked products. However, no significant difference in SO_2 removal was observed.

TABLE 7.3 COMPARISON OF SLAKED LIME PARTICLE SIZES

No.	Run Numbers For Which Lime was Used as Feed	Lime Source	Slaking Temperature (°F)	Slaking Water Quality	Mean Particle Diameter (µm)
1	801-805	Ash Grove	190	Process	4.4
2	806-810	Ash Grove	175	Process	4.4
3	811-815	Ash Grove	160	Process	3.5
4	816-820	Ash Grove	160	Sulfate-Doped	5.7
5	821-825	Ash Grove	160	Boiler Blowdown	3.6
6	826-830	Peter Lien	160	Process	4.5
7	831-835	Salida	160	Process	3.6
8(a)	836-840	Ash Grove	175	Process	4.1

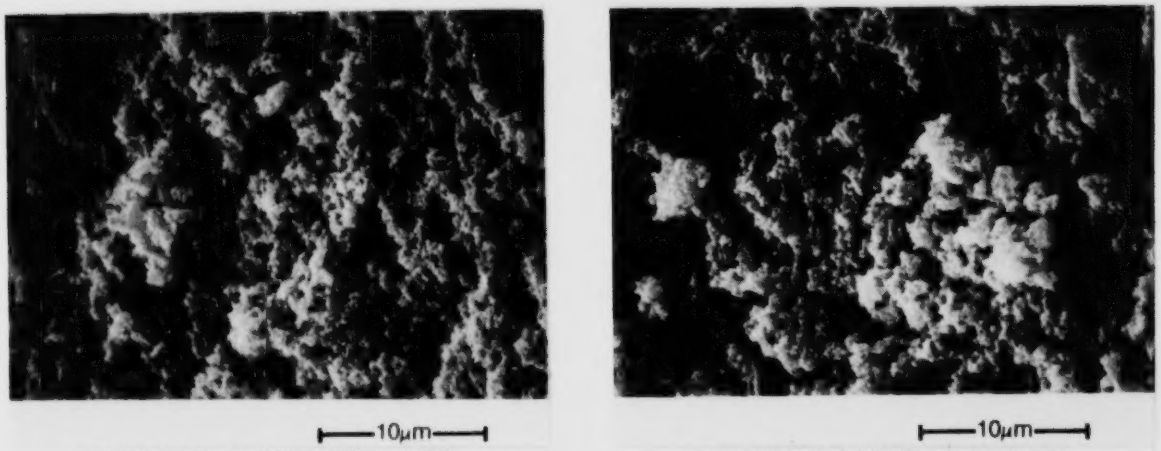
(a) Slaker paddle speed = 43 rpm

Scanning electron micrographs (SEMs) of the eight samples from the slaking tests are presented in Figure 7-9. The SEM photos were taken by Structure-Probe, Inc., with magnifications ranging from 300-30,000 X. The SEM photos indicate that seven of the eight samples are similar in appearance, having clusters of rounded and oblong particles of fairly uniform size. The SEM photo of the slaked Peter Lien quicklime (S-826) reveals clusters of particles that are more angular and crystalline in appearance. In general, better slaking results in finer particles of hydrated lime which increase the surface area of $Ca(OH)_2$ available for reaction with SO_2.



1. ASH GROVE, SLAKING TEMP. = 190°F

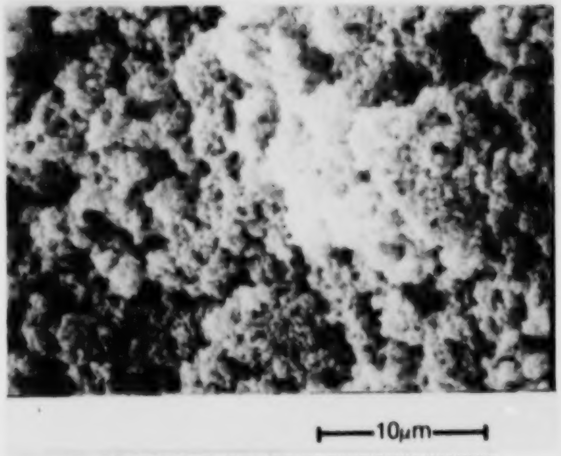
2. ASH GROVE, SLAKING TEMP. = 175°F



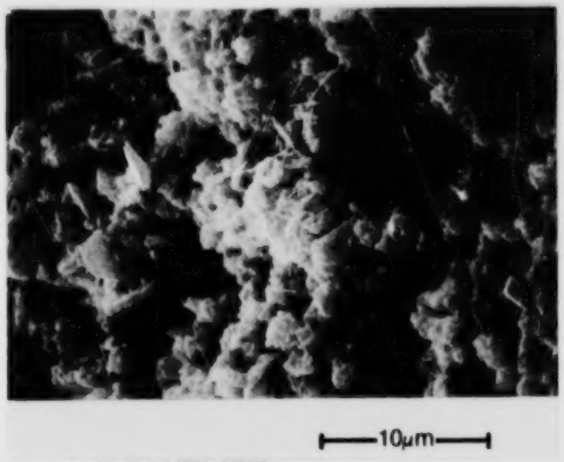
3. ASH GROVE, SLAKING TEMP. = 160°F

4. ASH GROVE, SULFATE-DOPED WATER

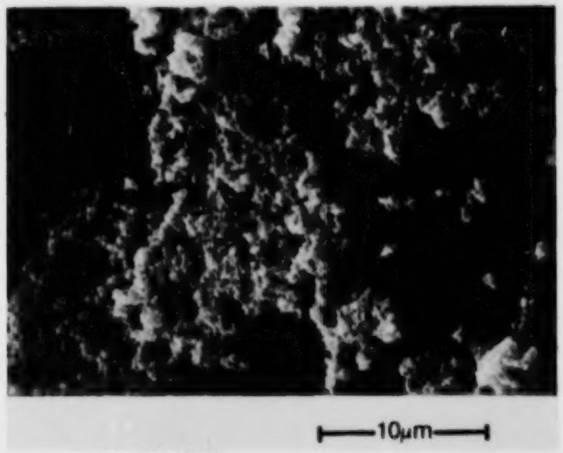
Figure 7-9. Slaked Lime Scanning Electron Micrographs.



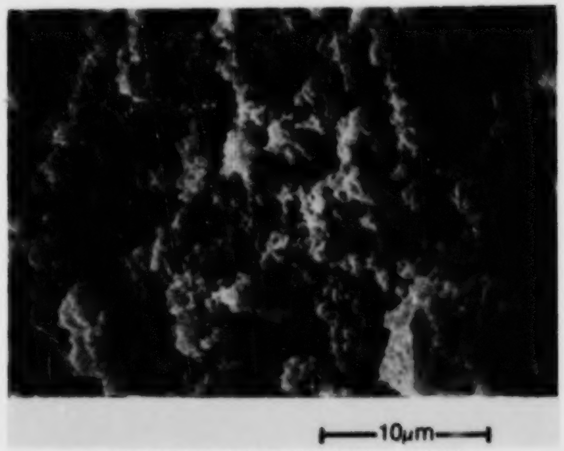
5. ASH GROVE, BOILER BLOWDOWN WATER



6. PETER LIEN LIME



7. SALIDA LIME



8. ASH GROVE, PADDLE SPEED = 43 RPM

Figure 7-9. (cont.) Slaked Lime Scanning Electron Micrographs.

SECTION 8

PROCESS DEMONSTRATION

PILOT TEST RESULTS

The concluding phase of the EPA-funded field test program was a continuous demonstration of the spray dryer/fabric filter technology. The demonstration run was conducted to verify that sufficiently high levels of SO_2 removal can be achieved on a sustained basis to meet the New Source Performance Standards (NSPS) operating on flue gas generated from Western low sulfur coal and lignite fuels. An initial demonstration run was begun on November 14, 1980, at a fixed set of operating conditions. After three days of continuous operation, the pilot unit was forced to shut down due to unseasonably cold weather at the Comanche Station. The unit was partially winterized and a new demonstration run was started on December 12, 1980.

Actual vs. Target Conditions

Essentially all of the targeted conditions of the demonstration run were well met, as shown in Table 8.1. In order to keep the inlet fabric filter flue gas temperature at approximately 50°F above the dew point of the flue gas, a portion of the hot flue gas was by-passed around the cooler and the spray dryer. Combining the by-passed flue gas with that from the spray dryer produces a mixture fed to the fabric filter that is higher in temperature, possesses a lower moisture content, and contains a greater SO_2 concentration than the flue gas exiting the spray dryer.

TABLE 8.1 ACTUAL VS. TARGET DEMONSTRATION RUN CONDITIONS

	Actual Average	Target
Spray Dryer Inlet Temperature, °F	271	270
Spray Dryer Outlet Temperature, °F	148	-
Spray Dryer Temperature Drop, °F	123	-
SD Approach to Adiabatic Saturation Temperature, °F	35	25
Fabric Filter Inlet Temperature, °F	201	200
FF Approach to Adiabatic Saturation Temperature, °F	45	58
Spray Dryer Inlet SO_2 Concentration, ppmv	480	520
Spray Dryer Residence Time, sec	9.1	10
Recycle Ratio, lb recycle solids/lb fresh lime	2.0	-
SO_2 Removal, %	68.8	70

The spray dryer outlet temperature during the demonstration was maintained higher than the 25°F approach to adiabatic saturation temperature target because a conservative approach was taken. During the demonstration, the approach to the adiabatic saturation temperature ranged from about 25 to 40°F with the average at 35°F. At this range of approach to adiabatic saturation, the stoichiometry requirements for a given level of SO_2 removal are somewhat higher than that expected at a 25°F approach temperature. Also, the stoichiometries used in the demonstration run to achieve 70 percent removal tend to be higher than those expected in a full-scale system where the process parameters are controlled more closely than was possible in the pilot plant.

Earlier pilot tests showed that at least a 25°F approach to adiabatic saturation temperature is required at Comanche to limit solids buildup, prevent plugging of the spray dryer hopper discharge, and insure long-term operation. It has been found that long-term operation is achievable when the moisture content of the spray dryer solids is no more than 15-20 wt. percent.

Overall Results

A 5-day (120-hour) continuous demonstration run was successfully conducted without interruption. The continuous operation demonstrated that a spray dryer/fabric filter pilot system is able to consistently achieve desired SO_2 removal values with negligible operating problems.

In general, the spray dryer/fabric filter system operated very steadily and quite satisfactorily. Figures 8-1 to 8-6 show the levels and trends of key process parameters versus time. Overall SO_2 removal, the prime control factor, averaged 68.8 percent compared to the target value of 70 percent. The overall stoichiometric ratio ranged from 1.1 to 2.1, with a mean value of 1.6. The overall stoichiometry was increased somewhat during the middle portions of the demonstration run in order to maintain overall SO_2 removal at 70 percent.

Upon completion of the 120-hour continuous run, the system was shut down for inspection. The interior walls of the spray dryer, in both the cylindrical and conical sections, were very clean and covered by only a minimal coating of dry solids dust. The rotary discharge valve was completely free of solids. A small conical pile of solids had accumulated on the 90° elbow to the outlet gas duct but caused no operating problems.

Plugging of the initially clean holes in the rotary atomizer occurred during the process demonstration run. Of the 12 holes in the periphery of the rotary atomizer, only two were completely open ($\sim$180° apart). Two others were partially open and eight were completely plugged. The total slurry flow was redistributed through the remaining unplugged holes. No discernible effect on SO_2 removal was apparent from plugging of the atomizer slurry flow ports based on observations during the demonstration and from analysis of test results.

Spray Dryer

The performance of the spray dryer varied somewhat over the length of the demonstration run. For about the first two days, overall SO_2 removal and stoichiometric ratio were fairly steady, as Figure 8-1 shows. During the next

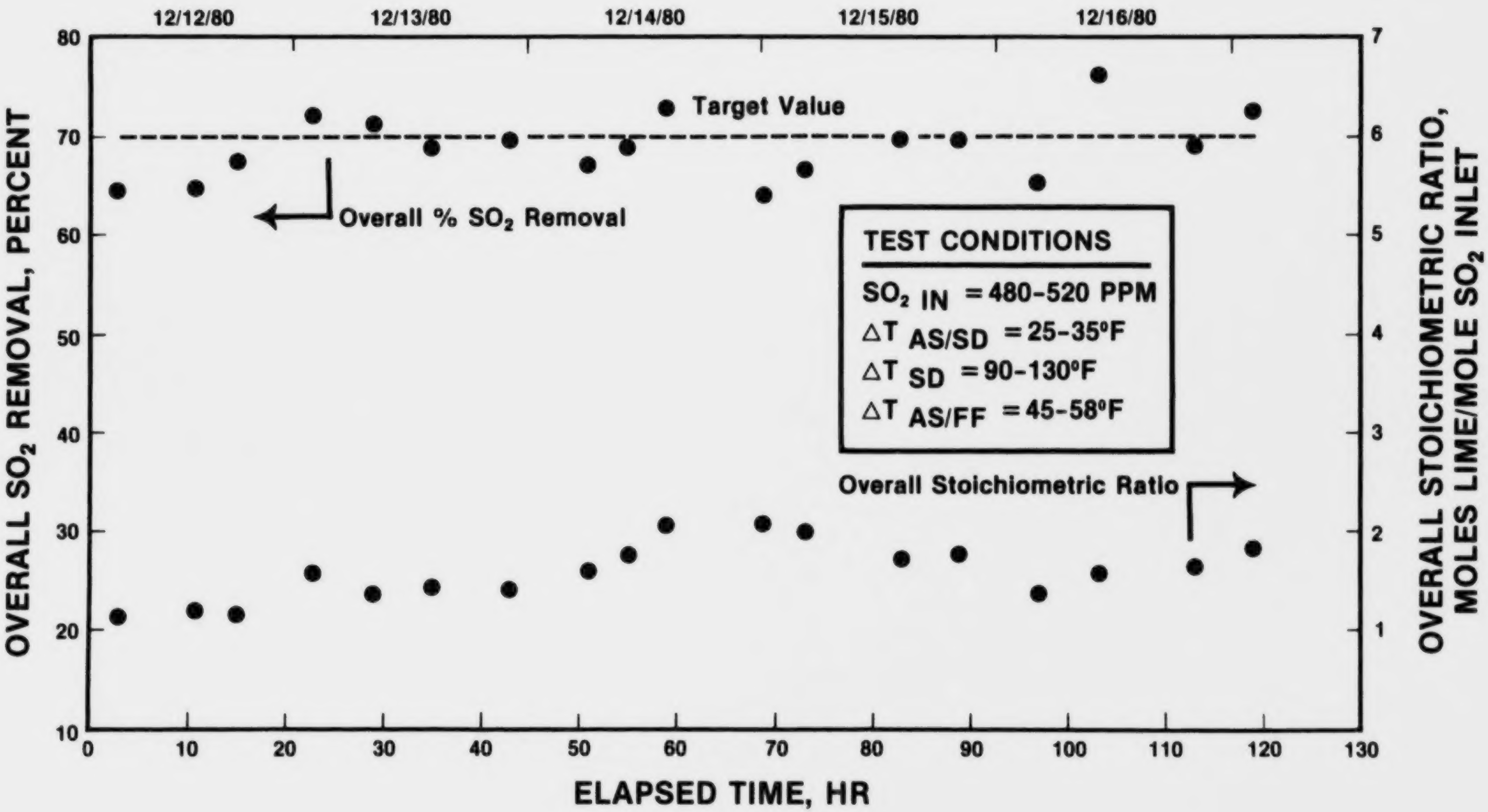


Figure 8-1. Process Demonstration Test Results - Overall SO_2 Removal and Overall Stoichiometric Ratio.

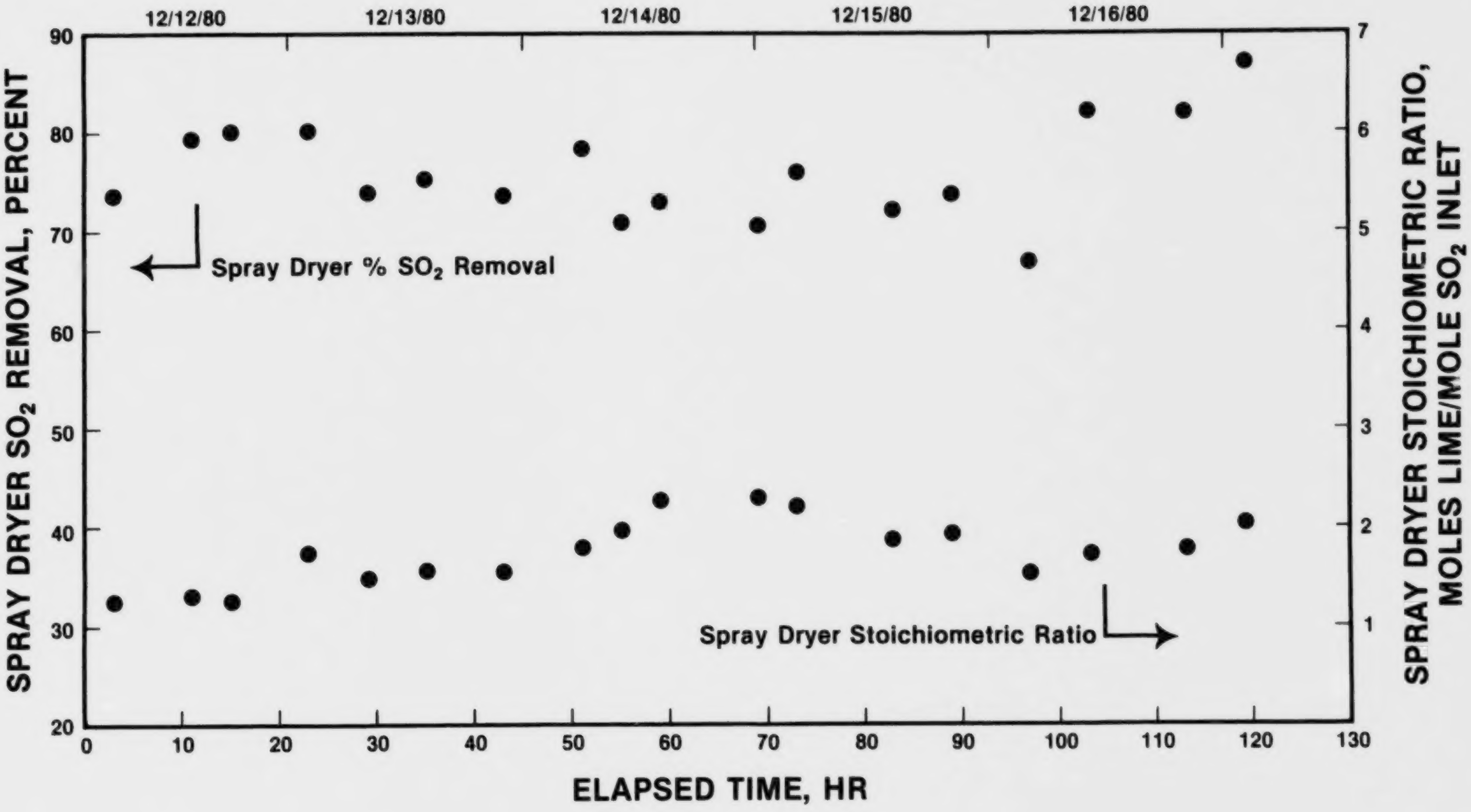


Figure 8-2. Process Demonstration Test Results- Spray Dryer SO$_2$ Removal and Spray Dryer Stoichiometric Ratio.

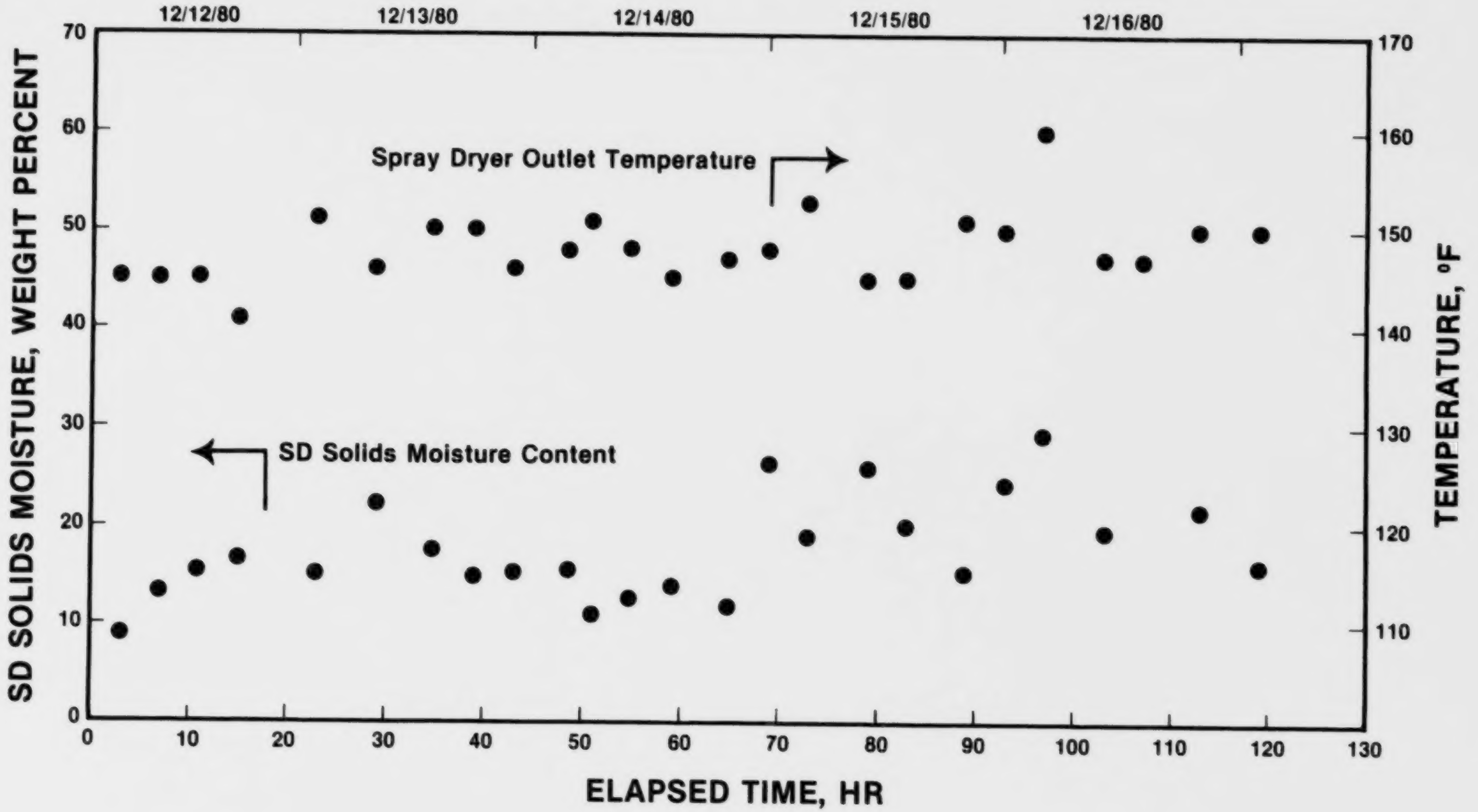


Figure 8-3. Process Demonstration Test Results-
Spray Dryer Outlet Temperature and Spray Dryer
Solids Moisture Content.

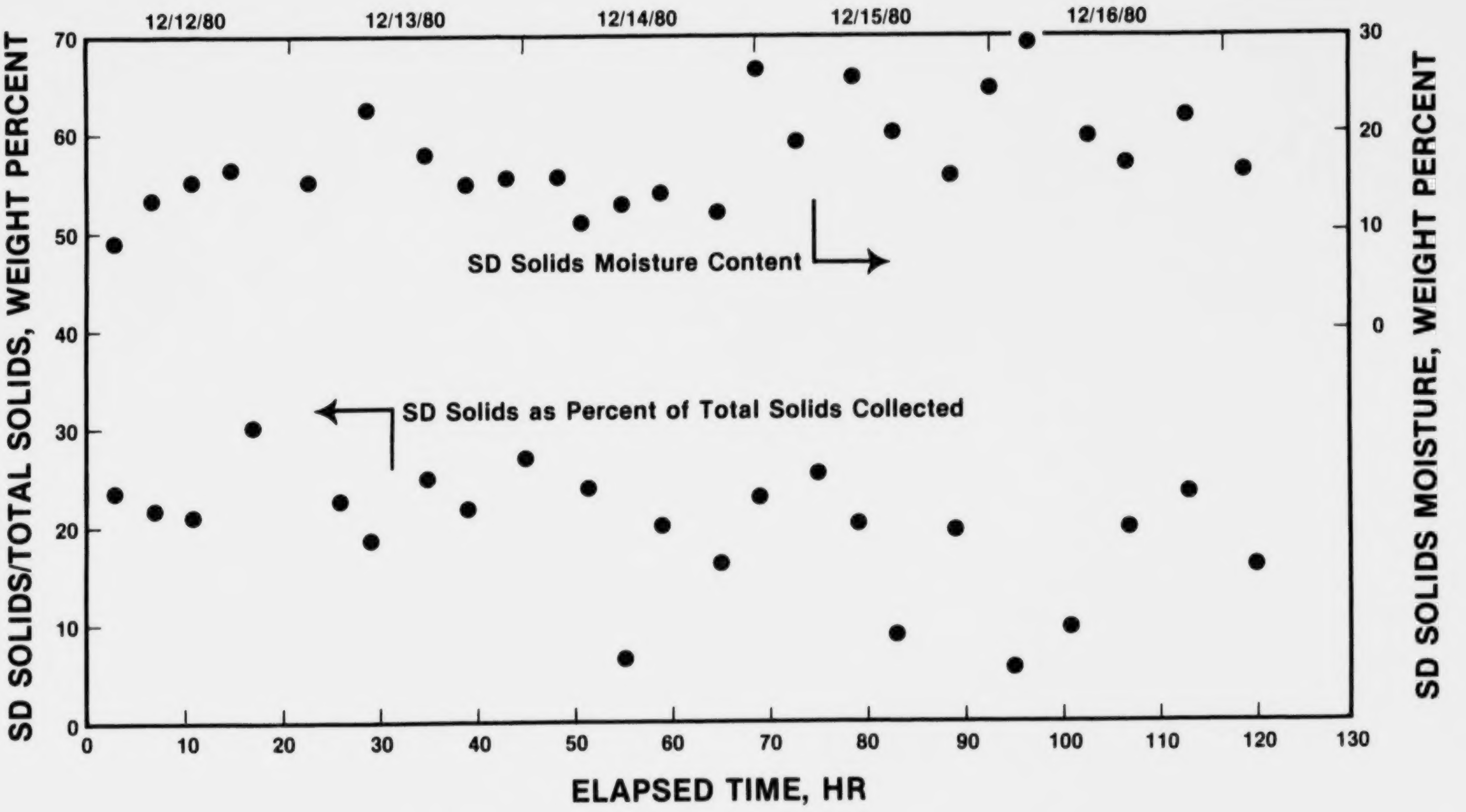


Figure 8-4. Process Demonstration Test Results- Spray Dryer Solids Moisture Content and Spray Dryer Solids as Percent of Total Solids Collected.

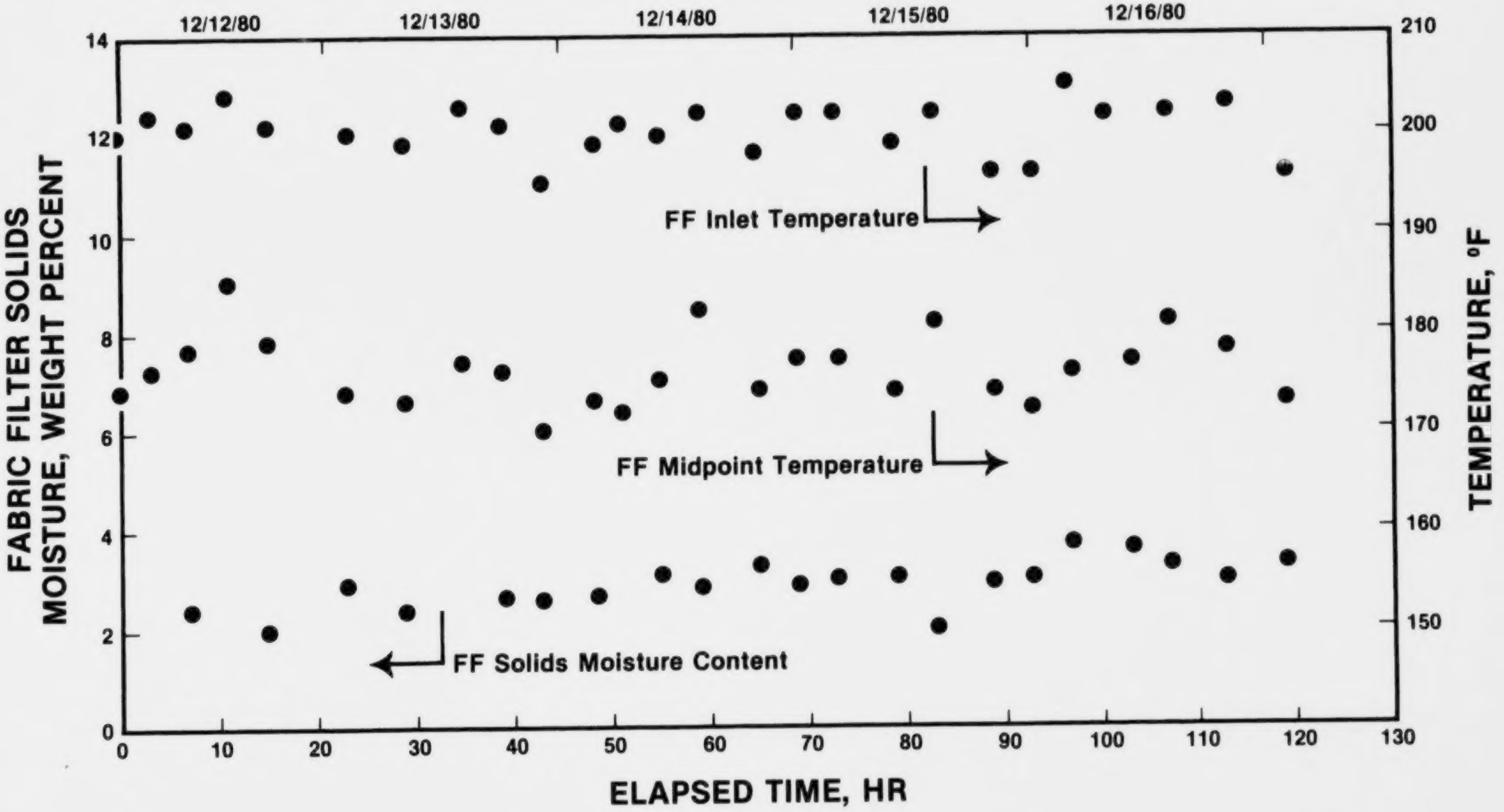


Figure 8-5. Process Demonstration Test Results-Fabric Filter Inlet and Midpoint Temperatures, Fabric Filter Solids Moisture Content.

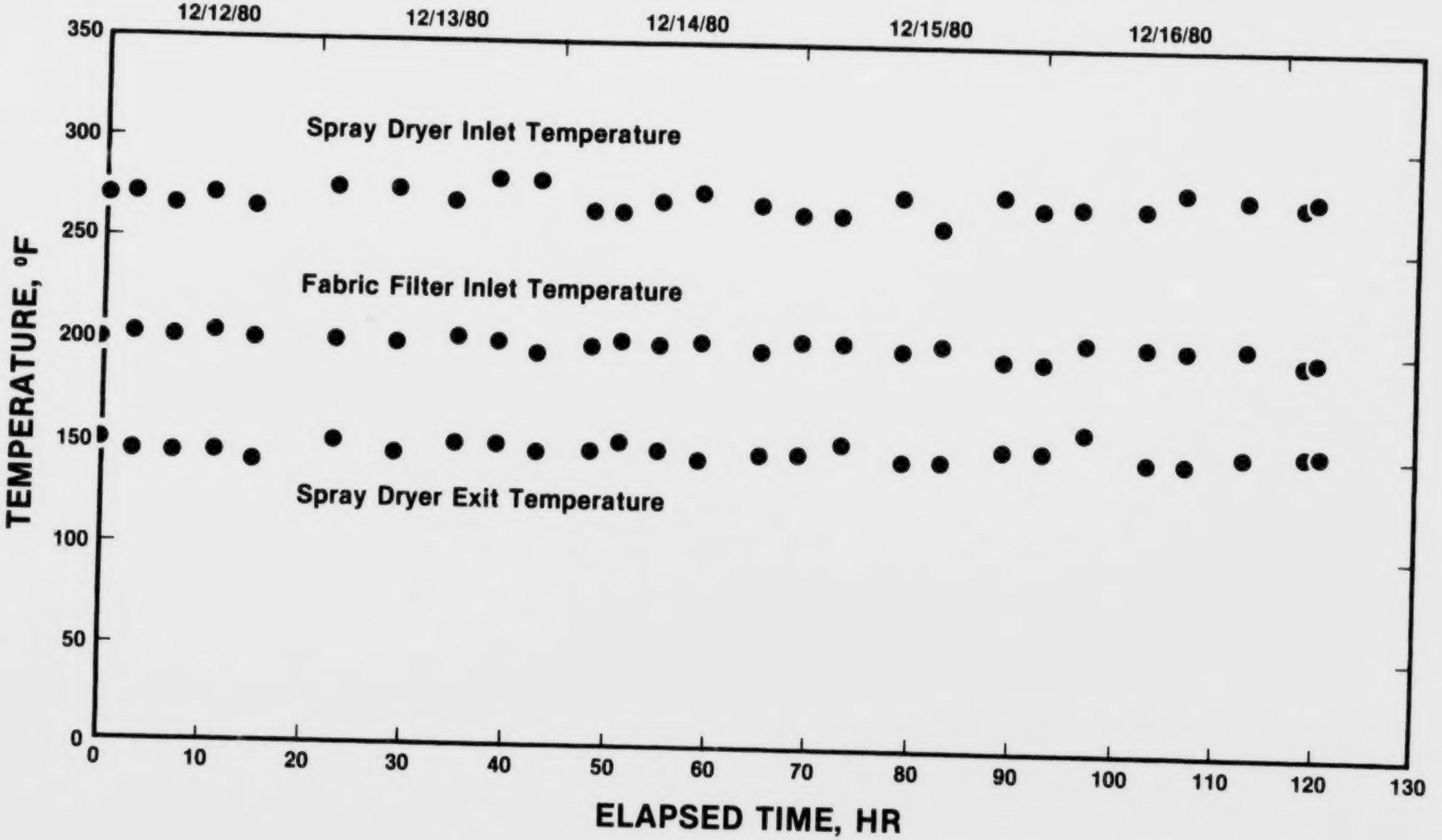


Figure 8-6. Process Demonstration Test Results-
Spray Dryer and Fabric Filter Inlet Temperatures,
Spray Dryer Exit Temperature.

two days, SO_2 removal performance decreased. In response to the reduction in SO_2 removal, the SR was increased. Also, the moisture content of the spray dryer product solids increased to 20-25 percent (Figure 8-3). In response to the increased moisture in the spray dryer solids, the spray dryer outlet temperature was increased from about 145°F to near 150°F which further decreased SO_2 removal performance. The percent of total solids which was collected as spray dryer product declined slightly to less than 20 percent during this same period (Figure 8-4).

The full explanation for the decrease in SO_2 removal performance in the spray dryer is not clear. Besides the increase of the spray dryer outlet temperature, two additional factors, which were not recognized during the run, contributed to poor performance of the spray dryer. They were:

1. A decrease in the adiabatic saturation temperature of up to about 5°F.

2. An inadvertent decrease in recycle ratio from about 2.0 to 1.6-1.8 lb recycle solids/lb fresh $Ca(OH)_2$.

During the final day of the demonstration run, SO_2 performance of the spray dryer increased from 70 to 75 percent to greater than 80 percent for no apparent reason. Moisture content of the SD solids dropped back to under 20 percent, and the percentage of solids collected from the spray dryer returned to about ∼20 percent of the total. The spray dryer stoichiometry remained in the range of 1.75-2.0, but the recycle ratio returned to higher levels.

Fabric Filter

The fabric filter performed consistently during the demonstration run. Inlet temperature to the fabric filter was maintained at 200°F by bypassing 19.5 percent of the total gas flow around the cooler and spray dryer. Fabric filter air-to-cloth ratio (based on inlet conditions) averaged 2.66 ft/min. Outlet temperature from the fabric filter ranged from 165 to 181°F. Heat loss in the fabric filter was not controlled but was governed by ambient conditions.

SO_2 removal in the fabric filter was low (0-5%) during the demonstration run since the fabric filter inlet temperature was maintained at 200°F to avoid filter bag blinding and pressure drop increases with the highly cementitious Comanche fly ash. At this temperature level, the reaction between SO_2 and unreacted reagent solids is sharply reduced because of the low solids moisture content ($< 3\%$).

Solids discharged from the fabric filter increased during the demonstration run from about 75 percent to 80+ percent of the total. Moisture content of the baghouse solids ranged from 2.0 to 3.7 percent H_2O (Figure 8-5). Moisture content also increased with time, probably due to the increase with time of the moisture in the solids leaving the spray dryer.

Pressure drop across the baghouse ranged from 2.0 to 4.0 in. H_2O and was very steady throughout the demonstration run. No variation at all was observed in the value of initial pressure drop for each cleaning cycle as it remained at

2.0 in. H_2O during the demonstration test. Time between cleaning cycles generally varied between 60 to 80 minutes but no trend was found. Thus quite satisfactory fabric filter performance and operation occurred during the five-day demonstration test at inlet temperatures in the range of 200°F.

SECTION 9

PRODUCT SOLIDS

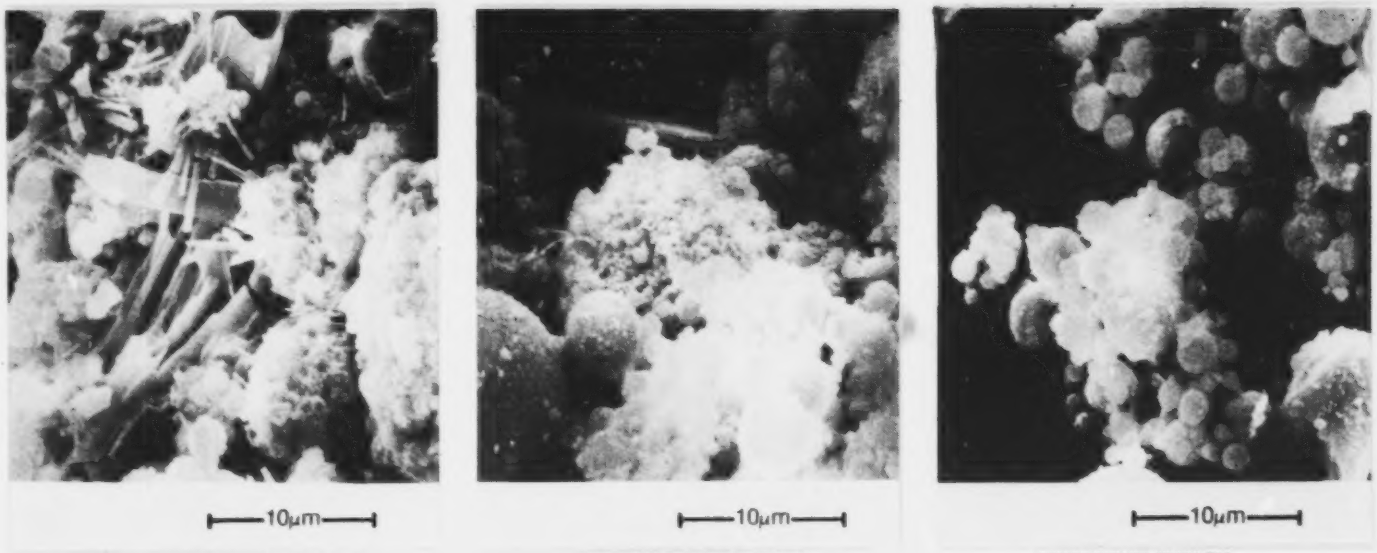
PRODUCT SOLIDS CHARACTERIZATION

Particle Size Distribution

The product solids collected in the spray dryer are coarser than those collected in the fabric filter. Table 9.1 shows the mean particle diameter and the geometric standard deviation of spray dryer and fabric filter solids obtained from pilot plant runs at a number of different operating conditions. Plots of comparisons of the spray dryer and fabric filter particle sizes on a run-to-run basis are presented in Appendix Figures B-5 to B-10. From these runs, the average mean particle diameter (50 wt. percent solids less than the mean value) of the spray dryer solids is about 30 to 35 µm and the average of fabric filter solids is about 10 µm. The fabric filter fly ash/FGD solids particle size approximates that of fly ash itself. The relative difference in particle size of the spray dryer and fabric filter solids is illustrated by the scanning electron micrographs of Figure 9-1. As shown in the SEM photos, the spray dryer solids tend to be composed of large discrete particles and agglomerates while the baghouse solids are comprised of smaller particles and show less agglomeration. For comparison, fly ash particulate is also depicted.

TABLE 9.1 PRODUCT SOLIDS PARTICLE SIZE DISTRIBUTIONS

		Spray Dryer Solids		Fabric Filter Solids	
Run Number	Operation Mode	Mean Particle Diameter (µm)	Geometric Standard Deviation (µm)	Mean Particle Diameter (µm)	Geometric Standard Deviation (µm)
105	Lime-Only	35.0	3.18	8.1	2.75
106	Lime-Only	26.2	3.20	9.8	2.89
115	Lime-Only	42.5	3.54	6.8	2.52
130	Lime-Only	19.0	3.65	11.0	3.33
603	Recycle	35.0	4.17	6.2	3.10
928	Recycle	39.0	5.00	14.0	4.00



SPRAY DRYER SOLIDS
RUN 603

FABRIC FILTER SOLIDS
RUN 603

COMANCHE FLYASH

Figure 9-1. Product Solids and Comanche Fly Ash Scanning Electron Micrographs.

Product Solids Collection

Product solids leave the dry SO_2 scrubbing system from both the spray dryer and the fabric filter. The relative amount of material collected at each location is a function of system operating parameters. As illustrated in Figure 3-2, the flue gas and particulate leaving the spray dryer must turn essentially 180° in direction in order to enter the outlet duct located near the bottom of the spray dryer. In turning, the larger, more agglomerated solids tend to collect in the spray dryer hopper while the finer particles are carried by the flue gas into the fabric filter.

The spray dryer solids consisted of a mixture of large discrete particles and agglomerates of flyash and FGD solids. Fabric filter solids are made up of finer individual particles and smaller agglomerates. Particulate size and the tendency to agglomerate appear to be related to the moisture content of the solids collected.

The fraction of total solids collected in the system that drops out in the spray dryer increases directly as the moisture content of the spray dryer solids increases (Figure 6-5). As Figure 6-5 shows, any effect of the system operating parameters that results in more moisture in the spray dryer solids appears to result in a larger fraction of total solids collected in the spray dryer bottom.

Product Solids Chemical Composition

The chemical composition of product solids collected from various runs during the pilot test program is shown in Table 9.2. (Overall reactions for the formation of the product solids compounds are given in Section 5.) The product solids were sampled from the material discharged from the spray dryer and fabric filter hoppers. All of the chemical analyses were performed in the Research-Cottrell Analytical labs. The analytical procedures are presented in Appendix C.

TABLE 9.2 PRODUCT SOLIDS CHEMICAL COMPOSITION
(Weight Percent)

Run Number	Source of Sample	Operation Mode	$Ca(OH)_2$	$CaCO_3$	$CaSO_3 \cdot \frac{1}{2}H_2O$	$CaSO_4$	Flyash	Total
105	SD	Lime-Only	6.28	18.06	1.40	7.66	N/A	N/A
105	BH	Lime-Only	5.16	9.37	N.D.	11.57	N/A	N/A
106	SD	Lime-Only	N.D.	21.06	0.55	5.77	N/A	N/A
106	BH	Lime-Only	11.20	10.23	12.33	9.26	N/A	N/A
115	SD	Lime-Only	N.D.	24.24	21.69	9.70	N/A	N/A
115	BH	Lime-Only	0.07	10.69	6.23	7.46	N/A	N/A
130	SD	Lime-Only	N.D.	16.66	5.83	6.75	N/A	N/A
130	BH	Lime-Only	N.D.	13.55	10.73	10.42	N/A	N/A

TABLE 9.2 PRODUCT SOLIDS CHEMICAL COMPOSITION (CONT.)

(Weight Percent)

Run Number	Source of Sample	Operation Mode	$Ca(OH)_2$	$CaCO_3$	$CaSO_3 \cdot \frac{1}{2}H_2O$	$CaSO_4$	Flyash	Total
206	SD	Lime-Only	10.15	18.88	21.41	4.33	40.36	95.13
206	BH	Lime-Only	16.35	11.94	21.44	5.51	40.73	95.97
221	SD	Lime-Only	N.D.	41.85	35.59	1.79	13.55	92.78
221	BH	Lime-Only	14.78	15.47	41.73	4.37	21.37	97.72
301	SD	Lime-Only	5.35	24.02	26.06	4.88	30.84	91.15
301	BH	Lime-Only	5.05	15.56	27.05	11.97	30.35	89.98
325	SD	Lime-Only	17.15	17.06	32.56	3.29	21.51	91.57
325	BH	Lime-Only	10.06	11.05	33.02	15.85	29.62	99.60
405R2	SD	Recycle	1.19	6.28	18.84	6.79	72.03	105.13
405R2	BH	Recycle	3.41	4.09	16.18	11.50	57.05	92.23
415	SD	Recycle	0.58	12.10	19.45	5.10	68.26	105.49
415	BH	Recycle	3.94	6.23	19.15	8.53	55.21	93.06
422	SD	Recycle	1.60	10.10	18.23	7.34	54.10	91.37
422	BH	Recycle	3.98	4.82	20.54	10.29	52.78	92.41
425	SD	Recycle	0.52	9.37	20.12	7.17	70.56	107.74
425	BH	Recycle	N.D.	6.23	19.40	9.73	56.87	92.23
501R	SD	Lime-Only	N.D.	18.24	24.94	4.96	56.02	104.16
501R	BH	Lime-Only	5.28	7.78	20.76	4.35	51.97	90.14
508	SD	Lime-Only	N.D.	18.33	25.86	4.05	51.54	99.78
508	BH	Lime-Only	N.D.	8.73	18.18	7.99	59.67	94.57
512	SD	Lime-Only	2.99	20.33	28.54	3.05	47.47	102.38
512	BH	Lime-Only	2.28	9.19	16.11	5.17	73.75	106.50
530	SD	Lime-Only	2.42	21.88	25.71	6.38	50.60	106.99
530	BH	Lime-Only	12.13	7.28	18.87	5.47	46.75	90.50
535	SD	Lime-Only	N.D.	18.10	26.90	6.89	45.15	97.04
535	BH	Lime-Only	11.82	9.27	22.10	6.49	43.16	92.84
603	SD	Recycle	N.D.	6.25	21.46	4.35	73.48	105.54
603	BH	Recycle	5.55	5.97	19.52	5.53	61.91	98.48
624	SD	Recycle	2.98	10.52	18.23	3.33	58.10	93.16
624	BH	Recycle	4.83	5.23	18.87	4.75	61.52	95.20
905	SD	Lime-Only	3.08	5.12	17.79	6.60	65.39	97.98
905	BH	Lime-Only	1.61	5.69	18.02	8.74	49.32	83.38
928	SD	Recycle	N.D.	4.21	32.08	6.29	40.98	83.56
928	BH	Recycle	2.26	7.90	26.49	10.51	39.17	86.33

N.A. = Not Available
N.D. = None Detected

TYPING GUIDE SHEET

Spray dryer solids and fabric filter solids contain roughly the same composition for a given run, according to Table 9-2. Spray dryer solids generally contain more unused reagent, especially calcium carbonate; fabric filter solids are relatively higher in calcium sulfate content. Most of the unused reagent is converted to $CaCO_3$, but some remains as $Ca(OH)_2$. Solids produced during the recycle runs generally are less alkaline ($Ca(OH)_2$ + $CaCO_3$ content) than are those collected from the lime-only runs because of higher reagent utilization in the recycle mode of operation. Increasing the stoichiometry increases the concentration of $Ca(OH)_2$ and $CaCO_3$ in the product solids because reagent utilization is decreased.

The fabric filter solids contain more $CaSO_4$ than do the spray dryer solids, reflecting the increased chances for oxidation as the solids remain in the system for a longer period of time. For the same reason, solids produced in the recycle runs generally contain more $CaSO_x$ constituents than do solids produced in lime-only runs.

The relative amounts of fly ash and FGD solids in the mixture collected in the spray dryer and fabric filter depend primarily on three factors:

1. Fly ash grain loading in the flue gas entering the dry scrubbing system
2. SO_2 concentration of the flue gas
3. Lime stoichiometric ratio.

Fly ash grain loadings of 1.0 to 2.5 grains/actual cubic foot (dry) were measured in the flue gas at Comanche Station. The amount of FGD solids collected is directly related to the arithmetic product of the incoming flue gas SO_2 concentration and the lime stoichiometric ratio used in a particular run to remove SO_2. SO_2 levels experienced varied from 185 to 2150 ppm while stoichiometric ratios tested ranged from about 0.5 to 6.0 moles slaked lime/mole SO_2 fed to the spray dryer.

For a given stoichiometry, the amount of FGD solids on a weight basis depends on the extent of conversion of lime to sulfur products, i.e., reagent utilization, during dry SO_2 scrubbing. The weight of FGD solids collected is also slightly affected by the lime converted to calcium carbonate by reaction with CO_2 and by the degree of oxidation that occurs. The extent of the oxidation reaction determines the ratio of calcium sulfite to calcium sulfate found in the product solids. The sulfite/sulfate ratio of the product solids in dry SO_2 scrubbing is significantly greater than is generally found in wet FGD scrubbing. The larger ratio indicates that considerably less oxidation occurs in the dry scrubbing systems where conditions are not as favorable as they are in wet FGD systems.

Product Solids Mineral Analysis

No strong trends or significant differences are apparent in the mineral analyses of spray dryer and fabric filter solids produced in the same run. Table 9.3 shows the results of mineral analyses performed on spray dryer solids from selected runs; Table 9.4 shows the results for the corresponding fabric filter samples. The mineral analyses were performed in the Research-Cottrell analytical laboratory.

TABLE 9.3 SPRAY DRYER SOLIDS MINERAL ANALYSIS

(Weight Percent)

	Run Number					
Constituent	106	206	425	501R	624	928
SiO_2	14.26	11.86	23.87	18.95	17.83	15.63
Al_2O_3	4.90	4.03	9.91	7.30	10.20	9.79
TiO_2	0.52	0.30	0.72	0.62	0.99	1.08
Fe_2O_3	1.95	1.44	2.41	2.20	3.05	3.93
CaO	48.88	50.11	36.48	38.57	36.11	34.40
MgO	1.35	1.06	2.51	2.13	3.05	2.90
Na_2O	0.57	0.49	0.90	0.76	1.03	1.18
K_2O	0.10	0.13	0.33	0.17	0.21	0.51
SO_3	3.39	2.54	4.21	2.91	1.96	3.70
P_2O_5	0.30	0.28	0.40	0.27	1.17	0.49
SO_3(iodometric)	1.71	13.28	12.48	15.47	11.30	19.89
LOI	15.10	17.18	4.22	6.97	11.51	2.85
Undetermined	6.97	-	1.56	3.68	1.59	3.65
Total	93.03	102.70	98.44	96.32	98.41	96.35

TABLE 9.4 FABRIC FILTER SOLIDS MINERAL ANALYSIS

(Weight Percent)

	Run Number					
Constituent	106	206	425	501R	624	928
SiO_2	10.14	13.86	19.24	17.58	18.88	14.94
Al_2O_3	6.61	7.49	11.11	10.05	9.63	10.46
TiO_2	0.61	0.65	0.89	0.81	0.93	1.18
Fe_2O_3	2.18	2.81	2.79	2.79	3.47	4.14
CaO	51.15	46.98	38.64	42.45	38.36	36.07
MgO	2.05	2.10	3.00	2.90	2.29	3.44
Na_2O	0.65	0.76	1.08	0.93	0.84	1.33
K_2O	0.08	0.14	0.20	0.17	0.22	0.59
SO_3	5.44	3.23	5.71	2.55	2.78	6.18
P_2O_5	0.47	0.65	0.53	0.43	0.70	0.77
SO_3(iodometric)	7.64	12.84	12.21	12.87	11.70	16.43
LOI	9.74	8.38	2.87	2.57	3.90	0.12
Undetermined	3.24	0.11	1.73	3.90	6.30	4.35
Total	96.76	99.89	98.27	96.10	93.70	95.65

PRODUCT SOLIDS REACTIVITY

Recycle Solids Source

Tests were performed to investigate the effect of the source of the recycle solids on SO_2 removal across the spray dryer. That is, recycled solids from the spray dryer and recycled solids from the fabric filter were compared for SO_2 removal.

As shown in Figure 9-2, the source of the recycled solids appears to have a negligible effect on SO_2 removal. Recycling either spray dryer solids or fabric filter solids produces essentially similar results. At a SR = 1.0, SO_2 removal increased from 38 percent to 50 percent as recycle ratio (RR) increased from 0 to 2.5, regardless of the type of material recycled. At a SR = 2.0, SO_2 removal increased from 49 percent to 60 percent as recycle ratio varied from 0

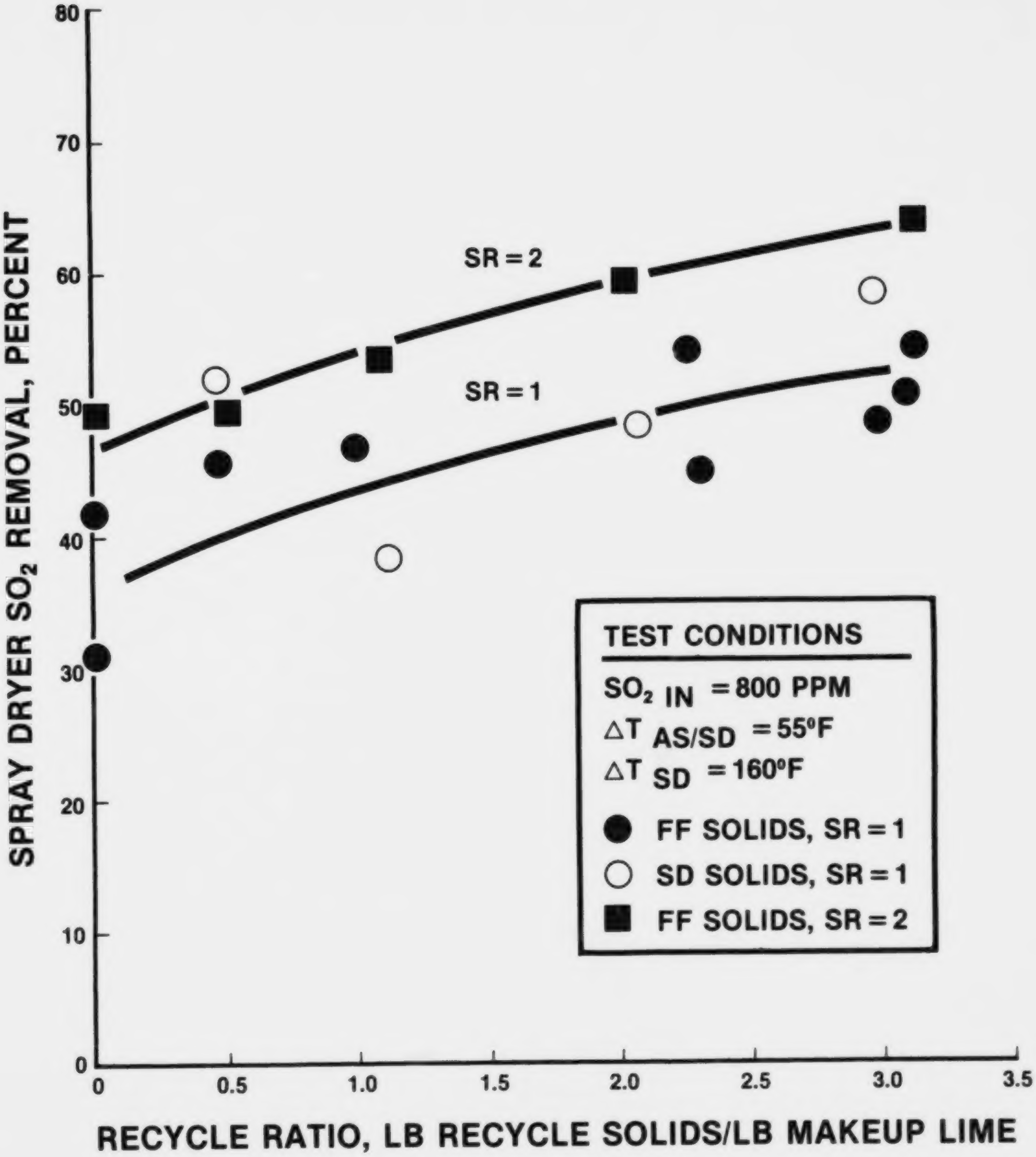


Figure 9-2. Effect of Recycle Solids Source on Spray Dryer SO_2 Removal.

to 2.5.

Dry solids products collected from the spray dryer and fabric filter contain a mixture of FGD products (calcium sulfite, calcium sulfate), various forms of unreacted reagent (quick lime, hydrated lime, and calcium carbonate), and flyash. Solids are collected at the bottom of the spray dryer and the bottom of each of the two compartments of the fabric filter. The solids deposited in the spray dryer hopper are collected by settling and dropping of particles from the flue gas. These solids are larger in particle size than the solids remaining with the flue gas transported to the fabric filter.

Virtually all of the FGD solids and flyash remaining in the flue gas leaving the spray dryer is collected in the fabric filter. The split of solids collection between the spray dryer and fabric filter depends on operating conditions as they relate to solids moisture content. The efficiency of particle collection in the fabric filter was treated as an incidental variable in the pilot plant studies.

Ball Milling Recycle Solids

The effect of ball milling recycle solids on SO_2 removal was also investigated. Dry solids were milled prior to reslurrying. Milling was performed continuously at an average residence time of 30 minutes as recommended by the ball mill vendor. Three types of solid materials were milled: spray dryer solids, fabric filter solids, and flyash alone.

Ball milling of recycle solids, at the conditions used in the pilot tests, has no significant effect on spray dryer SO_2 removal (see Figures 9-3 and 9-4). Despite some data scatter, no difference in performance is evident using either milled or unmilled solids for recycle. Also, as indicated previously, the source of the recycle material has no effect on SO_2 removal. Recycle solids from the spray dryer and baghouse yield similar results.

Particle size distributions of solid samples taken before and after ball milling reveal only minimal differences as shown in Figures 9-5 to 9-7. Scanning electron micrographs of the samples also showed no differences. Ball milling of the solids continuously using a 30-minute residence time apparently is insufficient to accomplish particle size reduction. Thus, it is not surprising that ball milling of recycle solids at the conditions used had no effect on SO_2 removal. Table 9.5 summarizes the results of the analyses by providing the mean particle diameters.

TABLE 9.5 EFFECT OF MILLING ON RECYCLE SOLIDS

	Mean Particle Diameter (μm)	
Solids Sample	Unmilled	Milled
Flyash	8.8	8.5
Spray Dryer Product	10.4	8.7
Fabric Filter Product	8.8	10.6

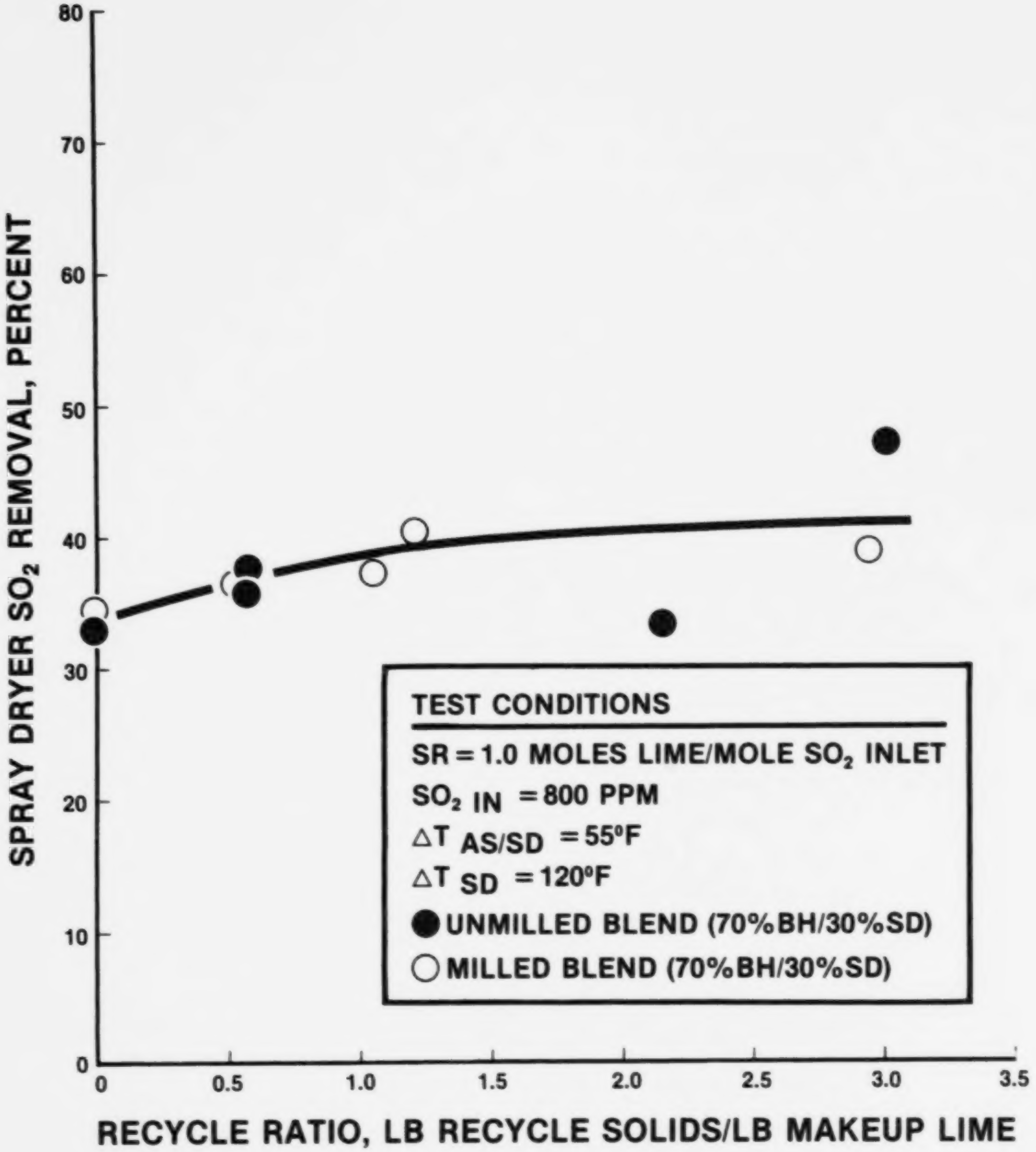


Figure 9-3. Effect of Ball Milling Recycle Solids Blend on Spray Dryer SO_2 Removal.

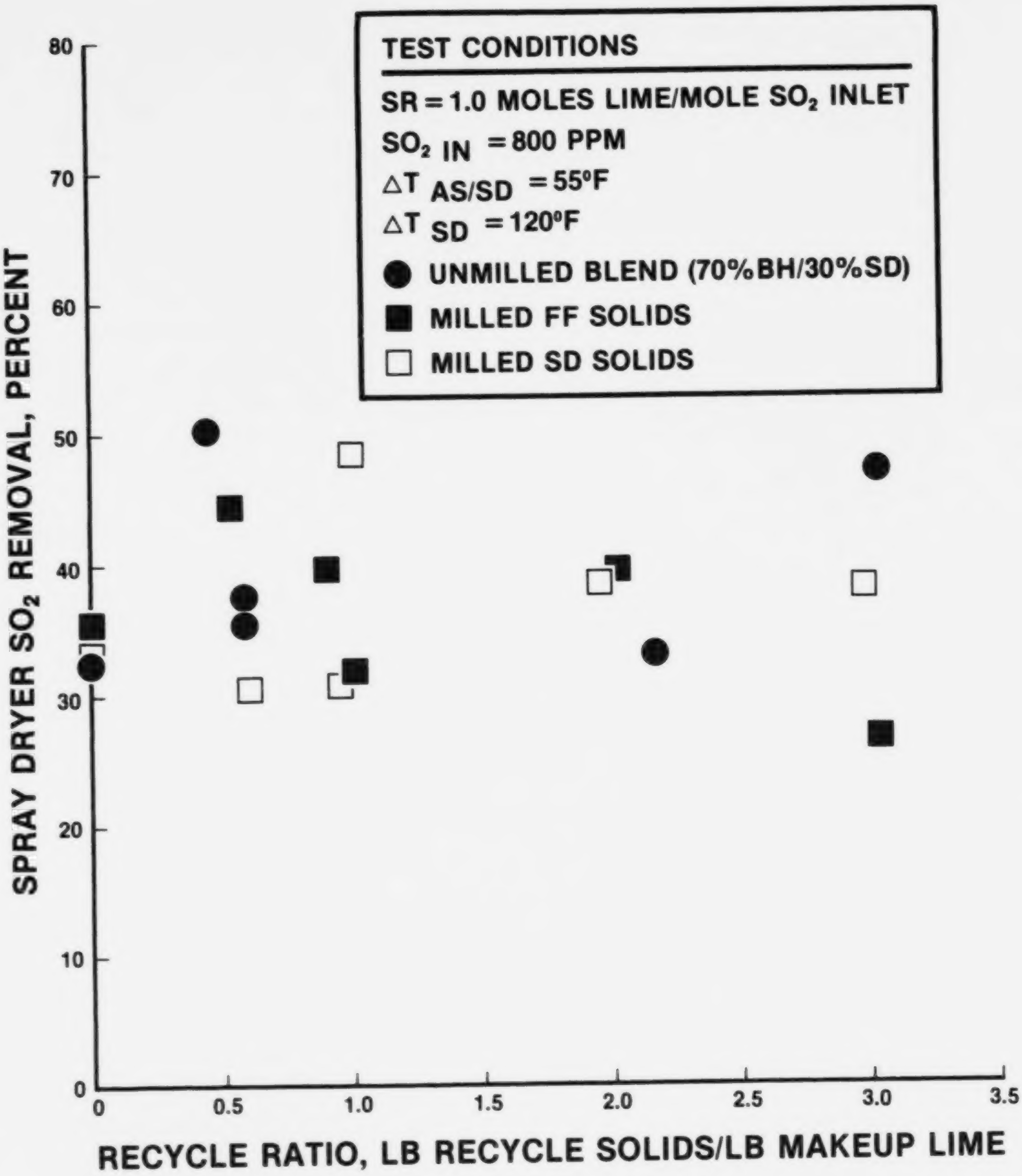


Figure 9-4. Effect of Ball Milling Recycle Spray Dryer and Fabric Filter Solids on Spray Dryer SO_2 Removal.

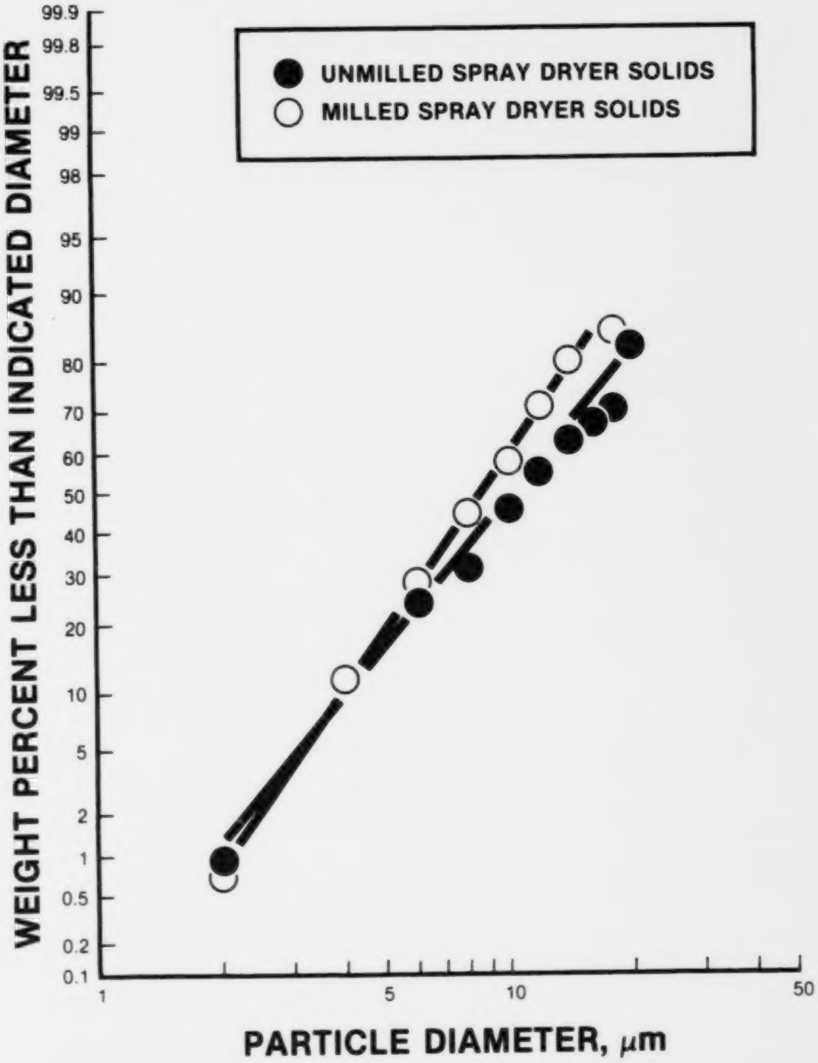


Figure 9-5. Effect of Ball Milling on Spray Dryer Particle Size Distribution.

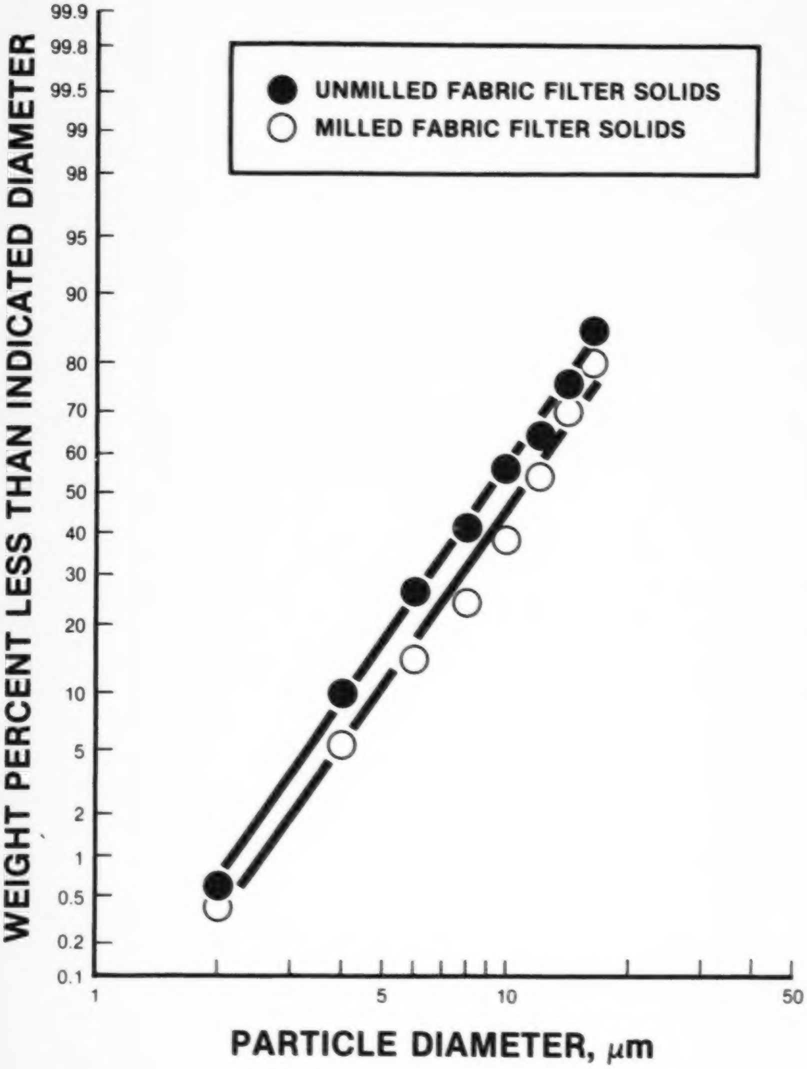


Figure 9-6. Effect of Ball Milling on Fabric Filter Particle Size Distribution.

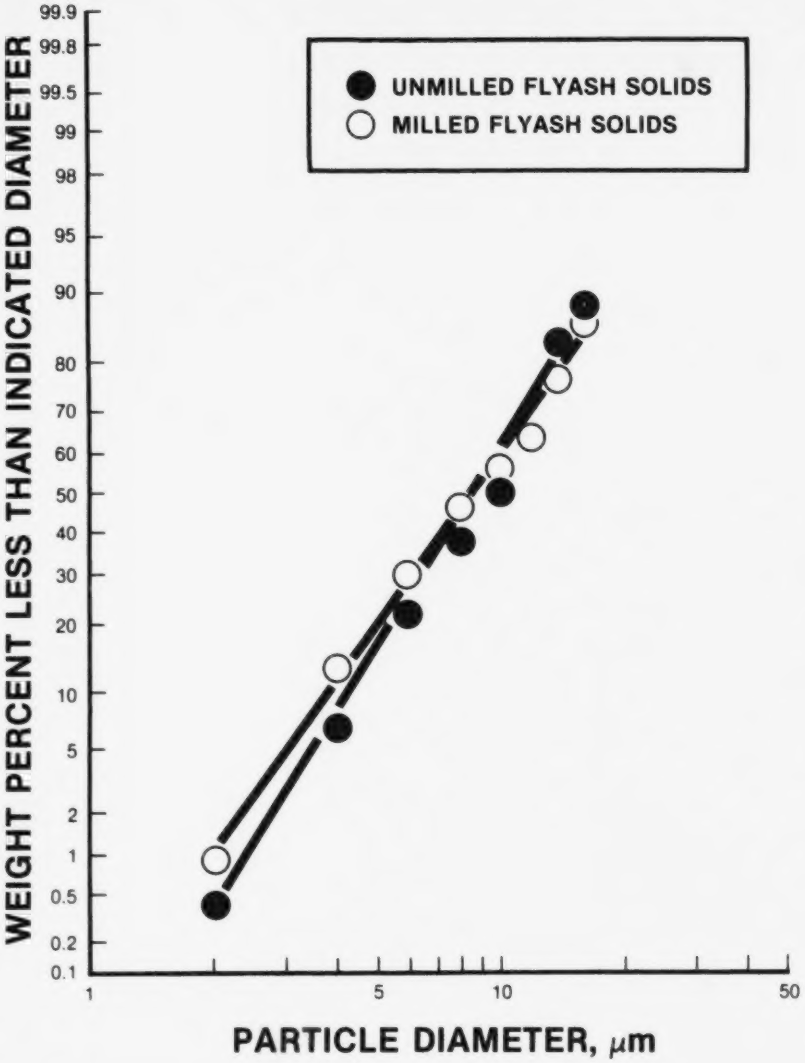


Figure 9-7. Effect of Ball Milling on Fly Ash Particle Size Distribution.

Flyash Reactivity

Flyash from the Powder River Basin coal burned at the Comanche Station is high in alkalinity content. A number of tests was conducted to determine the effectiveness of slurried flyash alone (no lime reagent) to remove SO_2 from the flue gas. Slurried flyash fed to the spray dryer removes significant amounts of SO_2 (see Figure 9-8). Percent SO_2 removal in the spray dryer increases directly as the amount of flyash added (available alkalinity) is increased. SO_2 removal of up to about 25 percent is achieved at an available alkalinity value of about 1.5 moles alkali/mole SO_2 by feeding only flyash slurry to the spray dryer.

Available alkalinity is defined as moles of available alkali in the flyash added per mole of SO_2 entering the spray dryer. Available alkali includes the molar sum of all CaO, MgO, Na_2O and K_2O values present in the flyash minus the moles of SO_3 present. The reported values of available alkalinity were calculated from fly ash analyses presented in Appendix B. It is very likely that not all of the alkali content in the flyash is available for reaction. Available alkalinity is used as a correlating parameter to indicate the effect of fly ash alkalinity on SO_2 removal.

Overall SO_2 removal also is directly related to the alkalinity of the flyash, as Figure 9-9 illustrates. Overall SO_2 removal ranged up to 30 percent at the highest levels of flyash alkalinity tested.

Although significant percentages of SO_2 removal are obtained in the dry SO_2 scrubbing system using flyash alone as the reagent, it does not necessarily follow that flyash alkalinity and fresh lime alkalinity are additive or interchangeable. That is, one should not take the results of Figure 9-9 as a basis to reduce the fresh lime stoichiometry needed to achieve a given level of SO_2 removal. If fresh lime is present, this source of reagent appears to be predominant over the alkalinity in the flyash for SO_2 removal. The effect of flyash alkalinity under these conditions appears limited. Fly ash alkalinity becomes more available for reaction if the lime reagent is nearly fully utilized, e.g., at low stoichiometric conditions where lime utilization approaches 100 percent.

Recycle Solids Reactivity

The effectiveness of reslurried recycle solids alone on SO_2 removal was also investigated. Recycle solids contain unreacted reagent as well as alkalinity available from the fly ash. Pilot tests were conducted feeding recycled solids slurry but no fresh lime to the spray dryer.

Based on Figure 9-10, SO_2 removal increases linearly with the amount of recycled solids fed to the spray dryer atomizer. On a pound-for-pound basis, flyash is more effective in capturing SO_2 than are recycle solids. However, Figure 9-11 indicates that SO_2 removal across the spray dryer correlates fairly well with the available alkalinity of these two kinds of solids. Only a slightly higher percentage SO_2 removal is achieved with fly ash alone than with recycle solids alone, based on Figure 9-11. For the recycle solids, available alkalinity contains a contribution from the unreacted reagent present. Thus,

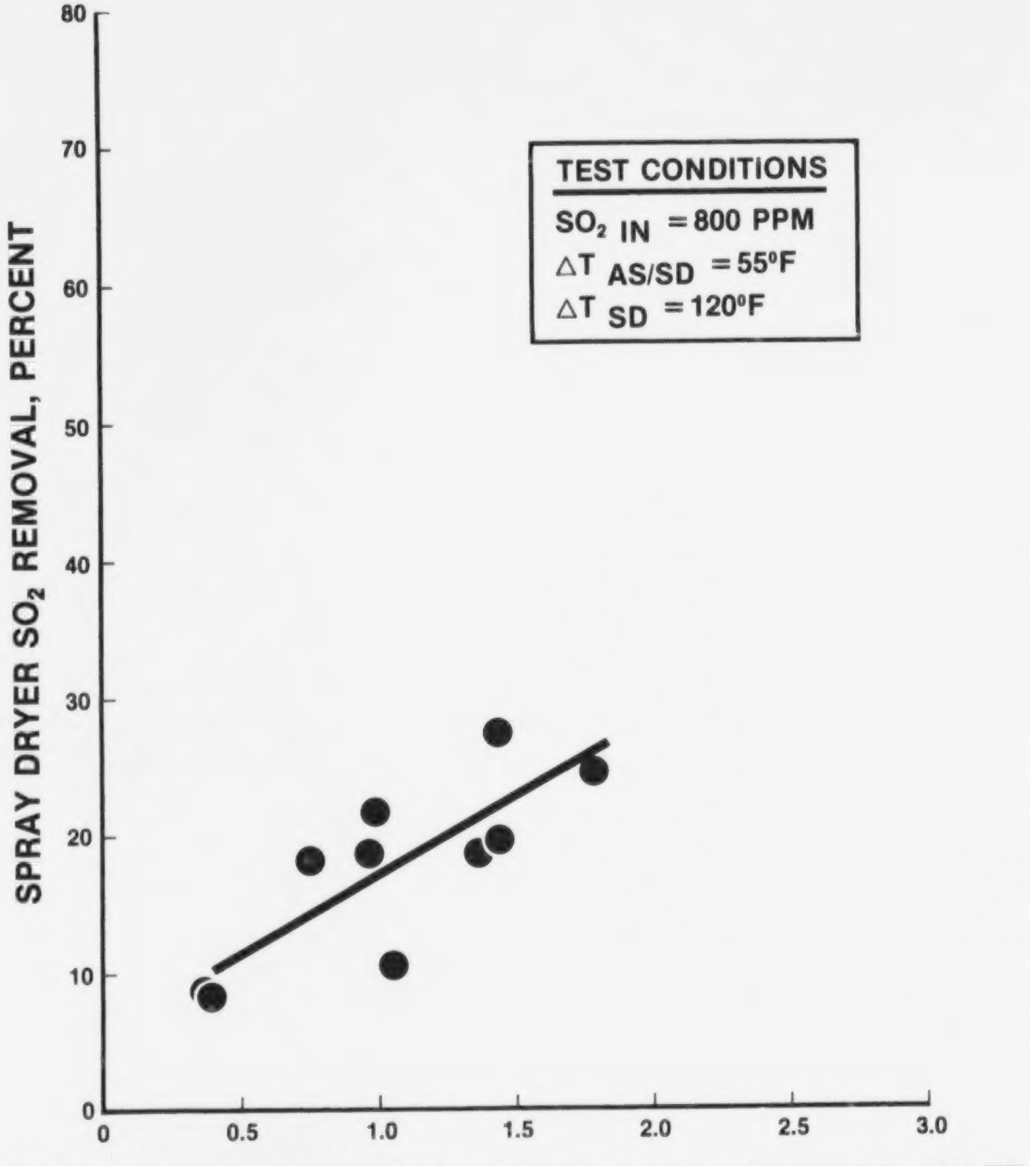


Figure 9-8. Fly Ash Reactivity for Spray Dryer SO_2 Removal.

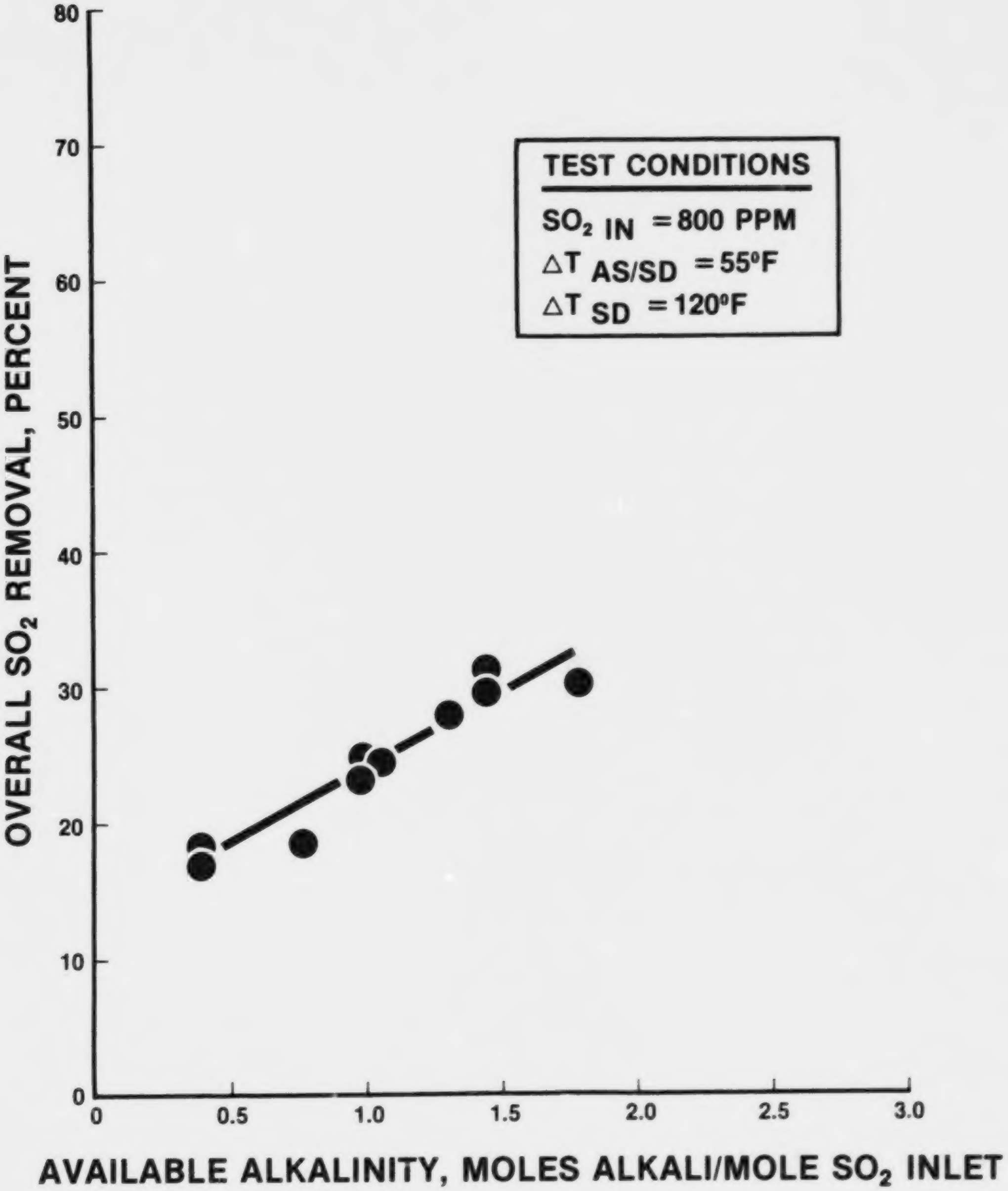


Figure 9-9. Fly Ash Reactivity for Overall SO_2 Removal.

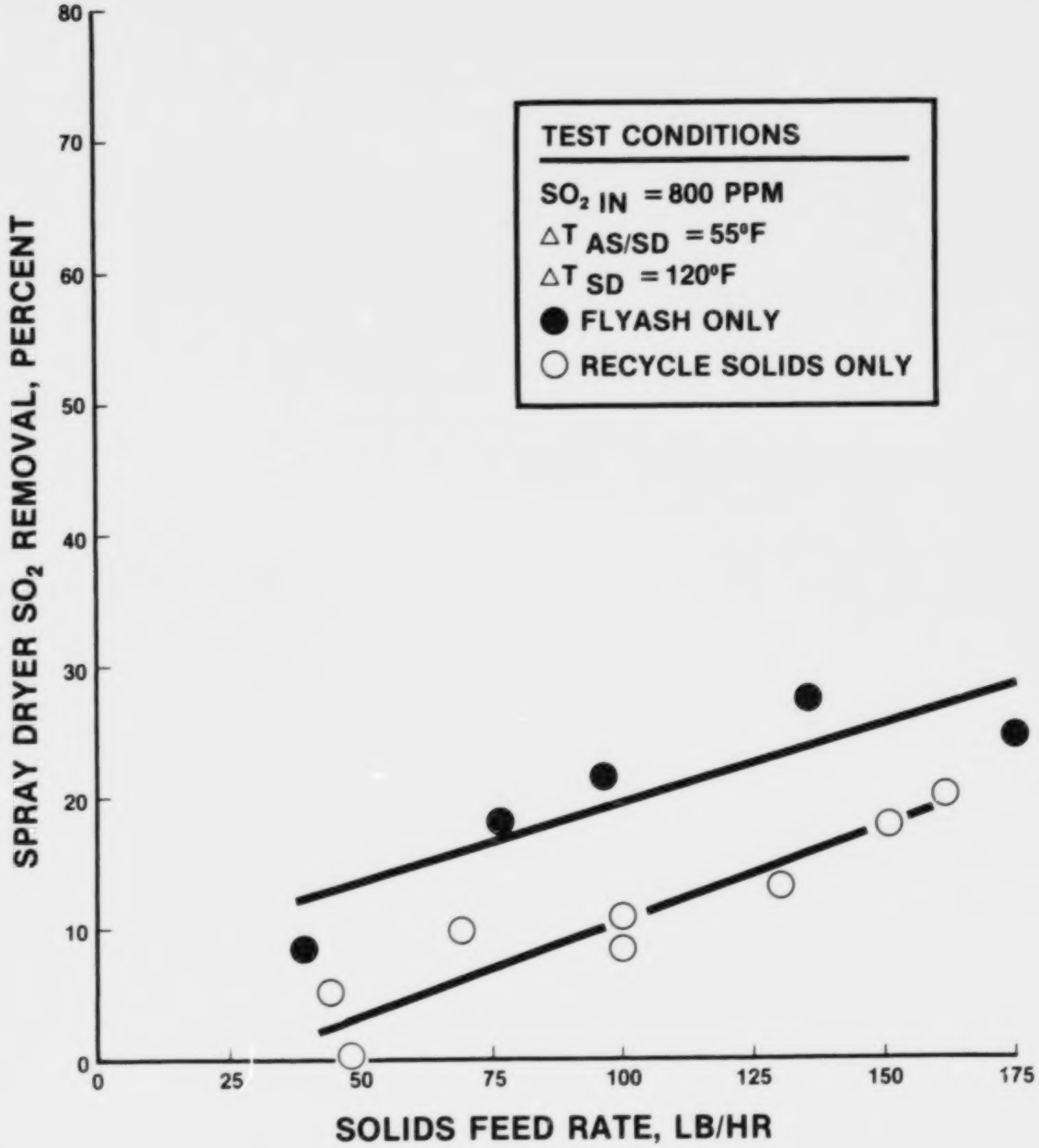


Figure 9-10. Recycle Solids Reactivity for Spray Dryer SO_2 Removal.

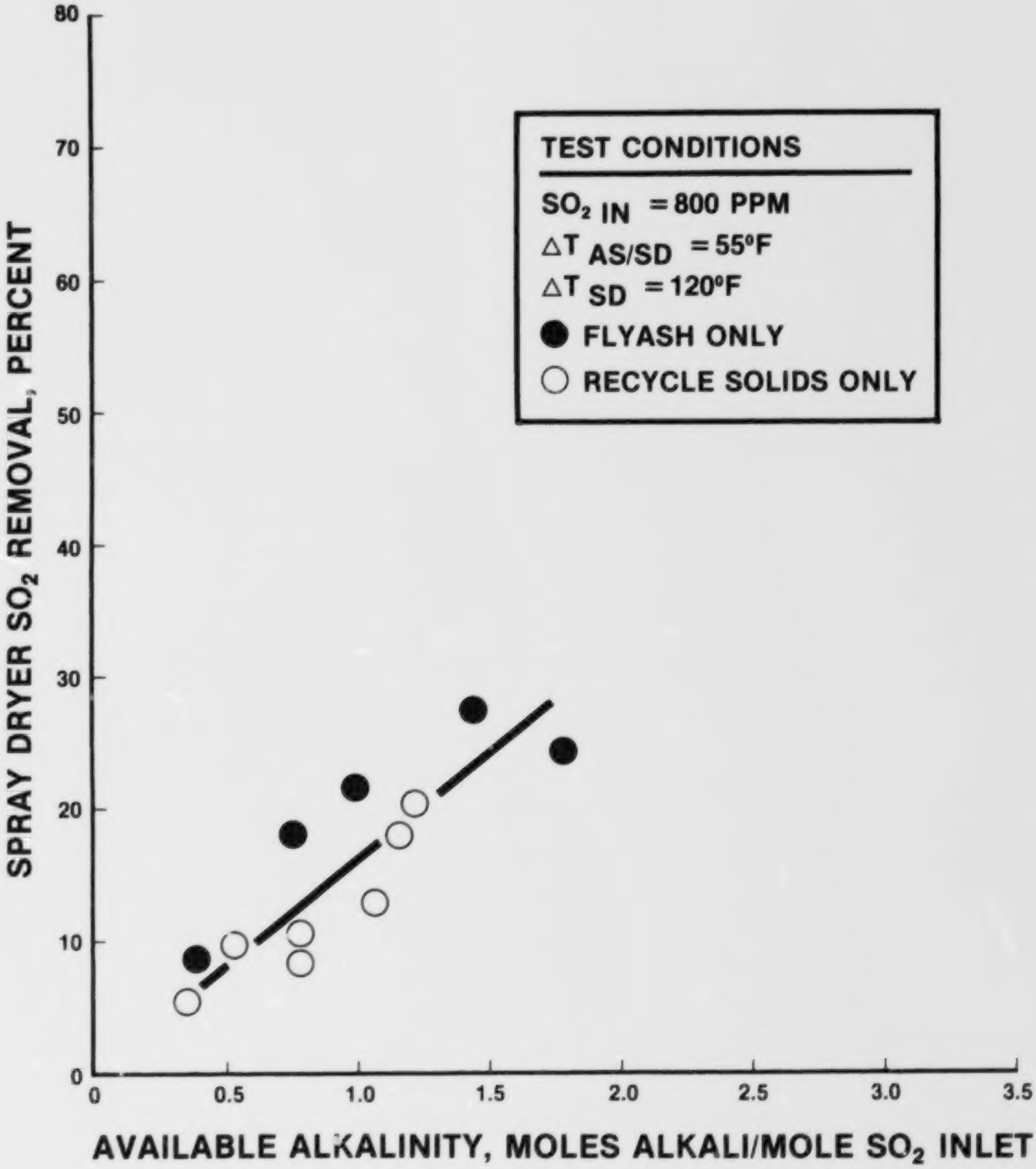


Figure 9-11. Effect of Availability Alkalinity on Spray Dryer SO_2 Removal.

in the range investigated, SO_2 removal increases directly with the amount of available alkali fed to the system. Significant SO_2 removal can be achieved by feeding reslurried flyash and/or recycle solids to the spray dryer in the absence of fresh lime feed.

SECTION 10

WASTE CHARACTERIZATION STUDIES

As part of the dry SO_2 scrubbing test program, a brief study was undertaken to characterize the solids wastes produced by the spray dryer/fabric filter dry scrubbing process. Only a modest amount of information has been published at the present time on the nature of the waste solids or their diposal characteristics. This limited investigation is intended to provide initial characterizations of the soil-mechanical and leaching properties of dry scrubbing waste solids.

The FGD solids/flyash samples were collected at the Comanche test site during the pilot runs and sent to CES laboratory facilites for the waste characterization tests. Care was exercised to preserve the "as taken" state of the samples and especially to prevent the gain or loss of water during transport and handling. To generate the samples, the pilot unit was operated under steady-state conditions at carefully chosen levels of stoichiometry and atomization until about 100 pounds of representative waste was collected. Product solids were acquired from both the spray dryer and the fabric filter.

A wide spectrum of operating conditions is represented in the runs sampled. The operating conditions for each of the runs in which samples were taken are summarized in Table 10.1. More details for these runs are presented in Appendix A. In most cases, a blend of 70 percent baghouse solids and 30 percent spray dryer solids (by weight) was tested. The 70/30 split is a normal product split for typical operating conditions, such as those given in Table 10.1. In three cases, fabric filter solids only were tested; in one other run spray dryer solids only were evaluated.

TABLE 10.1 OPERATING CONDITIONS FOR PILOT PLANT RUNS CHOSEN FOR WASTE CHARACTERIZATION SAMPLING

Run No.	Sample Source	Inlet SO_2 Concentration (ppmv)	Overall SO_2 Removal (%)	Stoichiometric Ratio (moles lime/ moles SO_2in)	Recycle Ratio (lb recycle solids/lb makeup lime)	Spray Dryer Temperature Inlet (^oF)	Spray Dryer Temperature Outlet (^oF)	$\Delta T_{AS/SD}$ (^oF)	Spray Dryer Residence Time (sec)
220	Blend	1350	39.4	3.01	0	268	188	71	10.0
314	Blend	1900	37.1	2.16	0	264	183	68	10.2
317	Blend	2150	43.1	1.05	0	345	185	70	10.4
405R2	FF	760	59.3	1.07	2.27	340	180	50	10.2
506	FF	850	50.9	2.01	0	258	178	48	9.5
624	Blend	780	39.9	1.04	1.06	295	177	48	9.9
923	SD	1380	72.2	1.14	2.62	255	147	22	9.4
923	FF	1380	72.2	1.14	2.62	255	147	22	9.4
923	Blend	1380	72.2	1.14	2.62	255	147	22	9.4

The FGD solids/flyash waste samples collected at the field test site were tested for the following soil-mechanical and leaching properties:

- o Compacted Density
- o Triaxial Compression
- o Permeability
- o Leachate Composition

Compacted Density

The proper evaluation of waste material intended for use as landfill must include certain basic soil-mechanical properties. The most important of these is the combined effect of water addition and compaction on the density of the waste material. Research-Cottrell, in the investigation of wet FGD sludge disposal, has employed ASTM D1557-70 test method in its laboratories to acquire these data.

Compacted densities of the dry SO_2 scrubbing waste samples were evaluated using ASTM procedure D1557-70. As shown in Table 10.2, the optimum moisture content for the dry scrubbing wastes is generally in the range of 25 to 35 wt. percent H_2O which corresponds to optimum densities in the range of 78 to 90 lb/ft^3. Solid wastes have a specific moisture content at which they can be compacted to their maximum density. At too low a moisture content, a negative pore pressure exists which pulls solids particles together and prevents them from sliding and compacting. Air voids are not filled with water or solids and density is reduced. At too high a moisture content, solid particles are replaced by water and the density is also decreased. At some intermediate moisture content, the solids attain a maximum density. At this point, compacted material tends to exhibit its maximum shear strength and minimum permeability.

TABLE 10.2 PRODUCT SOLIDS COMPACTED DENSITIES

Run Number	Operation Mode	Sample Source	Optimum Moisture (Wt. % H_2O)	Optimum Density (lb/ft^3)
220	Lime-Only	Blend(a)	30.0	86.9
314	Lime-Only	Blend	32.0	78.5
317	Lime-Only	Blend	40.0	68.6
405-R2	Recycle	Fabric Filter	24.0	91.5
506	Lime-Only	Fabric Filter	25.8	89.3
624	Recycle	Blend	26.0	87.6
923	Recycle	Spray Dryer	31.5	80.7
923	Recycle	Fabric Filter	28.5	80.0
923	Recycle	Blend	31.2	79.2

(a) Blend refers to a physical mixture of 70 wt. percent baghouse solids and 30 wt. percent spray dryer solids.

Compacted densities for the dry scrubbing waste products are lower and corresponding moisture contents are higher than the values found in previous studies by Research-Cottrell for sludge/flyash blends from wet FGD systems. Typical ash/sludge blends from a wet FGD system exhibit optimum densities in the range of 115 to 120 lb/ft^3 obtained at moisture contents in the range of 15 to 20 wt. percent.

The maximum compacted density values and corresponding optimum moisture water contents are developed to serve as basic engineering data for the determination of actual landfill area requirements and operating disposal procedures. However, the solids obtained from a dry scrubbing process sent to disposal probably will not be compacted to maximum density because of the cost involved.

Triaxial Compression

Triaxial compression testing yields values of material cohesive strength and angle of internal friction. From these values, the shearing strength is calculated using Coulomb's equation:

$$T_f = S \tan \phi + C \qquad (10\text{-}1)$$

where

T_f = Shearing Strength, psi
S = Normal Stress on the Shear Plane, psi
ϕ = Friction Angle, degrees
C = Cohesive Strength, psi

The information obtained from the triaxial compression tests for shearing strength can be used to evaluate the slope stability of materials for dike construction. Since both cohesion and internal friction interact to determine slope stability, the relative stability of the material cannot be evaluated by using either value alone. The suitability of the dry scrubbing wastes as dike construction materials is readily determined from conventional design calculations.

The triaxial compression tests were conducted at the New Jersey Institute of Technology under the direction of Dr. Paul Chan. Triaxial compression testing was performed in accordance with ASTM Standard D3397-75. The triaxial test is carried out with a lateral pressure of 10, 20, or 30 psi applied to the sample. The samples tested were first adjusted to their optimum moisture content by addition of water in accordance with the results obtained from the compacted density tests. Four of the samples were also cured for 28 days at constant temperature and relative humidity and then tested to determine the effect of curing.

The results of the triaxial compression tests are presented in Table 10.3. The cohesive strength and angle of internal friction for the samples collected under lime-only (no recycle) conditions are greater than the values for the waste products from the recycle runs. The cohesive strength of the lime-only products averages 16.1 psi compared to the recycle product average of 10.7 psi. Angle of internal friction averages 36.5 degrees for product runs with no recycle compared with 26.5 degrees for recycle runs solids. Since the runs with no recycle result in lower lime utilization than the recycle runs, the increased amounts of unused reagent present in the waste products may be expected to produce solids of increased strength.

As Table 10.3 also shows, both cohesion and angle of internal friction increase significantly from the uncured values after curing for 28 days. The solids exhibit some tendency to set with time because of the presence of unused reagent in the mixture.

TABLE 10.3 PRODUCT SOLIDS TRIAXIAL COMPRESSION TEST RESULTS

			Uncured		Cured(a)	
Run No.	Operation Mode	Sample Source	Cohesion (psi)	Angle of Internal Friction (degrees)	Cohesion (psi)	Angle of Internal Friction (degrees)
220	Lime-Only	Blend(b)	16.3	36	-	-
314	Lime-Only	Blend	18.2	39	110	51
317	Lime-Only	Blend	15.8	37	-	-
405-R2	Recycle	Fabric Filter	6.0	33	63	51
506	Lime-Only	Fabric Filter	14.0	34	63	48.5
624	Recycle	Blend	13.0	32.5	34	42
923	Recycle	Spray Dryer	12.0	24	-	-
923	Recycle	Fabric Filter	12.1	21	-	-
923	Recycle	Blend	10.2	22	-	-

(a) Cured for 28 days at 72°F and ~ 100% relative humidity.

(b) Blend refers to a physical mixture of 70 wt. percent baghouse solids and 30 wt. percent spray dryer solids.

Permeability

Permeability is a measure of the rate at which water or leachate passes through solids. The pollution potential of a waste is strongly determined by the permeability of the material to rainwater since it dictates the amount of leaching that occurs. Proper disposal site design enhances runoff and minimizes water permeation through the waste. The leachate from the disposal site flows into the ground water and eventually into streams, rivers, and lakes. Regulatory agencies commonly require information about the permeability of waste products before granting permits to build FGD and particulate control systems as well as disposal sites.

The rate of water passing through a sample of solids of a given cross section is proportional to the gradient applied, according to Darcy's Law:

$$q = KAi \qquad (10\text{-}2)$$

where:

q = Rate of Flow, cm^3/sec
K = Coefficient of Permeability, cm/sec
A = Cross Sectional Area of Flow, cm^2
i = Flow Gradient, cm/cm

The proportionality constant, K, is the coefficient of permeability, and it indicates the degree of permeability of the solids under consideration.

Permeability was measured with the constant head test (ASTM Method D2434-68). The permeabilities of four of the samples were also measured after curing to investigate the effect of curing on permeability.

As shown in Table 10.4, permeability values for uncured dry scrubbing products solids are of the order of 10^{-5} cm/sec. Curing the samples for approximately one month tends to decrease the permeability of the waste solids, based on the few samples examined. In two cases (Samples from Runs 506 and 624), the permeability of the material decreases significantly after curing. But in two other cases (Samples from Runs 314 and 405R2), the permeabilities of the samples before and after curing are very similar.

TABLE 10.4 PRODUCT SOLIDS PERMEABILITIES

Run No.	Operation Mode	Sample Source	Permeability Uncured (cm/sec)	Permeability Cured (cm/sec)
220	Lime-Only	Blend(a)	3.0 x 10^{-6}	-
314	Lime-Only	Blend	4.0 x 10^{-6}	3.5 x 10^{-6}(b)
317	Lime-Only	Blend	1.2 x 10^{-5}	-
405-R2	Recycle	Fabric Filter	2.0 x 10^{-6}	3.5 x 10^{-6}(c)
506	Lime-Only	Fabric Filter	3.3 x 10^{-5}	7.0 x 10^{-7}(d)
624	Recycle	Blend	8.9 x 10^{-5}	9.0 x 10^{-7}(d)
923	Recycle	Spray Dryer	7.1 x 10^{-5}	-
923	Recycle	Fabric Filter	9.3 x 10^{-5}	-
923	Recycle	Blend	5.3 x 10^{-5}	-

(a) Blend refers to a physical mixture of 70 wt. percent baghouse solids and 30 wt. percent spray dryer solids

(b) Cured for 35 days at 72°F and ∼ 100 percent relative humidity

(c) Cured for 38 days at 72°F and ∼ 100 percent relative humidity

(d) Cured for 28 days at 72°F and ∼ 100 percent relative humidity

Coefficients of permeability for stabilized materials from wet FGD systems vary over a wide range. Physically stabilized sludge/flyash blends possess permeability coefficients typically ranging from about 10^{-5} to as low as 10^{-8} cm/sec, depending on the free CaO content and other factors. Sludge/flyash blends stabilized with small percentages of lime typically exhibit permeability values of 10^{-7} to 10^{-8} cm/sec. The synthetic gypsum ($CaSO_4 \cdot 2H_2O$) solids stabilized by the oxidation of FGD sludge possess a coefficient of permeability of $\sim 10^{-4}$ cm/sec. The permeability of uncured waste from the dry SO_2 scrubbing process of $\sim 10^{-5}$ cm/sec approximates that of blended sludge/flyash material mixtures from a wet FGD process.

Leachate Composition

Leachate tests measure the concentration of dissolved solids picked up by water as it permeates through a layer of waste solids. Total dissolved solids (TDS) is the most frequently measured quantity, but major component concentration (i.e. sulfate, sulfite and chloride) and trace metal concentrations (often contributed by flyash) are also determined. Leachate test results along with permeability values are the factors commonly used to predict or evaluate the environmental effect of disposed FGD sludges and solids.

Waste material from the dry scrubbing process is likely to be disposed of as landfill. Environmental problems from the permeation of rainwater through waste solids are less likely for landfill disposal than for ponding since landfills are not subjected to the constant head of water as are ponded wastes.

Leachate samples from permeability tests were collected and analyzed for major component chemical composition. As Table 10.5 shows, the TDS content of the leachate generally exceeds 1200 ppm, and the bulk of it is attributable to $CaSO_4$. Mg^+, Cl^-, and $SO_3^=$ values are uniformly quite low. The general procedure for preparing a leachate of a solid is included in Appendix C, along with the analytical procedures for the chemical species.

TABLE 10.5 PRODUCT SOLIDS LEACHATE COMPOSITIONS

Run No.	Operation Mode	Sample Source	Total Dissolved Solids (ppmw)	Ca^{++} (ppmw)	Na^+ (ppmw)	Mg^+ (ppmw)	$SO_3^=$ (ppmw)	$SO_4^=$ (ppmw)	Cl^- (ppmw)	Alkalinity as $CaCO_3$ (ppmw)
220	Lime-Only	Blend[a]	1247	404	33	<1	N.D.[b]	91	-	1041
314	Lime-Only	Blend	1710	518	35	<1	N.D.	328	-	1097
317	Lime-Only	Blend	1527	484	20	<1	N.D.	276	-	987
624	Recycle	Blend	452	-	-	-	-	-	<1	-
923	Recycle	Spray Dryer	740	148	44	<1	N.D.	280	5	16
923	Recycle	Fabric Filter	1600	635	40	<1	N.D.	59	10	137
923	Recycle	Blend	1270	578	53	<1	N.D.	116	1	105

(a) Blend refers to a physical mixture of 70 wt. percent baghouse solids and 30 wt. percent spray dryer solids.

(b) N.D. = None Detected.

Potable drinking water standards in many states limit TDS to a 500 ppm maximum. In order to meet drinking water standards, the leachate from FGD solids at a disposal site can be reduced by proper landfill design and management. This objective is attainable by increasing the water runoff rate, decreasing the permeation rate through the disposed FGD wastes, and locating disposal sites where favorable hydrogeological conditions (i.e. low water table) exist.

Heavy Metals

Dry SO_2 scrubbing product solids were analyzed for heavy metals content as part of the waste characterization studies. Product solids collected from the process variable tests and the demonstration run were analyzed for the following heavy metal constituents: arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver. The leachates of spray dryer and fabric filter samples along with Comanche fly ash (Powder River Basin coal) also were analyzed for trace metals.

Spray dryer and fabric filter product solids from the present test program, analyzed by Radian Corporation for Electric Power Research Institute (EPRI) project RP1870-2 (Table 10.6), were found to contain ppm levels of heavy metal elements. Table 10.6 shows that the spray dryer and fabric filter solids contain about the same level of heavy metals. Trace metal contents of composite samples from several lime-only runs are comparable to those from the continuous demonstration run conducted under recycle conditions. Barium at 100 to 500 μg/g and chromium at up to 80 μg/g are present in the largest concentrations but the remaining elements exist at less than 15 μg/g.

TABLE 10.6 PRODUCT SOLIDS HEAVY METALS ANALYSIS[a]

	Runs 959--966 Composite (b)		Continuous Demonstration Run (c)(d)	
Constituent	Spray Dryer (μg/g)	Fabric Filter (μg/g)	Spray Dryer (μg/g)	Fabric Filter (μg/g)
Arsenic	<15	<15	<15	<15
Barium	310	140	120	300
Cadmium	< 2	< 2	< 2	< 2
Chromium	28	56	57	70
Lead	<15	<15	<15	<15
Mercury	< 8	< 8	< 8	< 8
Selenium	<20	<20	<20	<20
Silver	< 1	< 1	< 1	< 1

(a) Analyses performed by Radian, Inc. for EPRI Project RP1870-2.
(b) Lime-Only Runs
(c) See Section 8
(d) Preliminary Values

Table 10.7 presents the leachate analyses from dry scrubbing waste solids prepared and analyzed by Radian (EPRI project RP1870-2). Each of the heavy metals was present in the leachate at concentrations significantly less than the maximum allowable levels for extraction procedure toxicity of hazardous wastes (10-2). Only barium is present at a concentration of greater than 1 mg/l which is well below the maximum level of 100 mg/l. Buell/Anhydro (10-3) found comparably low heavy metal concentrations in leachates from a spray dryer/fabric filter product solids mixture from tests at the Martin Drake Station, Colorado Springs, Colorado. The Martin Drake Station boiler No. 6 from which flue gas was taken burns low sulfur northwest Colorado coal.

TABLE 10.7 PRODUCT SOLIDS LEACHATE HEAVY METALS CONTENT[a,b]

	Spray Dryer		Fabric Filter	
Constituent	EPA Extract[c] (mg/l)	Neutral Extract[d] (mg/l)	EPA Extract (mg/l)	Neutral Extract (mg/l)
Arsenic	<0.003	<0.003	<0.004	<0.004
Barium	4.0	2.5	0.54	0.2
Cadmium	<0.0005	<0.0005	<0.0005	<0.0008
Chromium	<0.005	0.12	0.10	0.16
Lead	<0.005	0.003	<0.002	<0.002
Mercury	<0.0002	<0.0002	<0.0005	<0.0002
Selenium	<0.004	<0.004	0.010	<0.004
Silver	<0.01	0.005	<0.002	<0.002

(a) Product samples obtained from Runs 959 to 966 of present test program.

(b) Analyses performed by Radian, Inc. for EPRI Project RP1870-2.

(c) EPA extraction procedure described in Federal Register, Volume 45, No. 98, 33127, May 19, 1980

(d) Neutral extraction procedure substitutes (volume/volume) water for acetic acid used in the EPA procedure.

Comanche pilot test solids were leached by Radian according to the EPA extraction procedure and a neutral extract procedure (See Table 10.7 for reference and description). Barium, chromium and silver were analyzed by ICAP (inductively coupled, argon plasma emission spectrometry) while the other heavy metals were analyzed by atomic absorption methods.

CES analyzed product solids leachates from Comanche pilot tests conducted using recycle operation (Table 10.8). Leachates from spray dryer and fabric filter solids (Run 405R2 -- recycle operation) contained heavy metals in the same trace ranges found in the EPRI work. Comanche flyash leachate metal contents also approximated the dry scrubbing waste solids concentrations, according to Table 10.8. This result indicates that fly ash is the main contributor to the heavy metals present in FGD solids/fly ash product solids mixtures.

TABLE 10.8 PRODUCT SOLIDS AND FLYASH LEACHATE HEAVY METALS

Constituent	Spray Dryer[a] (mg/l)	Fabric Filter[a] (mg/l)	Comanche Flyash[b] (mg/l)
Arsenic	0.0025	0.0028	0.0017
Barium	2.30	9.43	1.67
Cadmium	<0.004	<0.004	<0.004
Chromium	<0.025	<0.051	<0.23
Lead	<0.1	<0.11	<0.05
Mercury	<0.0002	<0.0004	<0.0002
Selenium	0.0013	0.0066	<0.0006
Silver	<0.007	<0.007	<0.007

(a) Run 405R2, recycle operation.
(b) Flyash sample collected in September 1980.

Leachate samples were prepared by CES according to the general procedure presented in Appendix C.5. Trace metal analysis was conducted in the CES laboratory using standard atomic absorption techniques (10-4, 10-5).

SECTION 11

TECHNOECONOMIC STUDY

INTRODUCTION

The success of the emerging new technology of dry SO_2 scrubbing depends on surmounting both technical and economic hurdles despite its attractive features such as simplicity and low water requirements. Pilot plant tests executed in the present program formed the basis for an economic evaluation of dry SO_2 scrubbing technology.

A technoeconomic study was performed to compare a dry SO_2 scrubbing system using lime reagent with wet FGD systems consuming limestone. The SO_2/particulate pollution control systems evaluated in this study include:

1. Spray dryer followed by a fabric filter (SD/FF)
2. Fabric filter followed by a single loop wet scrubber (FF/LS)
3. Electrostatic precipitator followed by a single loop wet scrubber (ESP/LS).

Capital investment and annual operating costs were estimated and compared for the three pollution control systems studied. In addition, sensitivity analysis elucidated the effect of system size (MW) and percent S in the coal on unit capital and unit operating costs. The effects of percent S in the coal and reagent price on lime reagent costs were also determined.

STUDY DESIGN BASIS

For the technoeconomic studies, a power plant located in Colorado was used as the basis since the pilot test work was performed at the Comanche Station of Public Service of Colorado in Pueblo. The Powder River Basin coal used in this study possessed a heating value of 8230 Btu/lb and contained 0.6 percent sulfur, 5.77 percent ash, and 30.5 percent water. The SO_2 and particulate removal efficiencies were based on New Source Performance Standards of 0.6 lb $SO_2/10^6$ Btu and 0.03 lb particulate/10^6 Btu. The system design basis was specified for these conditions and is presented in Table 11.1.

TABLE 11.1 STUDY DESIGN BASIS

Item	Design Value
1. Flue Gas Rate, acfm	2,040,000
2. SO_2 Inlet Concentration, ppm	600 - 1500[a]
3. Flue Gas Inlet Temperature, °F	275
4. Atmospheric Pressure, psi	12.3
5. SO_2 Removal Efficiency, %	70 - 80[a]
6. Particulate Inlet Content, grains/acf	2.3
7. Particulate Removal Efficiency, %	99.7

[a] Design basis for SO_2 removal was 70% at inlet SO_2 of 600 ppm, 90% at 1500 ppm.

DRY SO_2 SCRUBBING SYSTEM - SPRAY DRYER/FABRIC FILTER

Process Description

A process flow diagram for a typical dry SO_2 scrubbing system is presented in Figure 11-1. The two major pieces of equipment used in the process are the spray dryer, primarily for SO_2 removal, and the fabric filter, primarily for particulate removal. Other key equipment is required for materials handling, feed slurry preparation, gas handling, and waste solids disposal.

Flue gas enters the spray dryer where it contacts the atomized slurry composed of a mixture of fresh lime and recycled solids. Sulfur dioxide is absorbed into the slurry and reacts with the lime. The slurry rate and concentration are fixed such that the water injected into the spray dryer is completely vaporized but insufficient to saturate the flue gas. Part of the dry FGD solids/fly ash mixture is collected and discharged from the spray dryer bottom, but the majority of solids is carried by the flue gas to the fabric filter. Particulate removal and some additional SO_2 removal occur in the fabric filter, and the cleaned gas flows to the stack. Some of the dry solids mixture collected in the spray dryer and fabric filter hoppers is recycled and mixed with fresh lime slurry fed to the spray dryer. The remainder of the collected solids is sent to waste disposal.

Design Criteria and Assumptions

The system design criteria and assumptions are tabulated in Table 11.2. Table 11.3 is an equipment list for the spray dryer/fabric filter system.

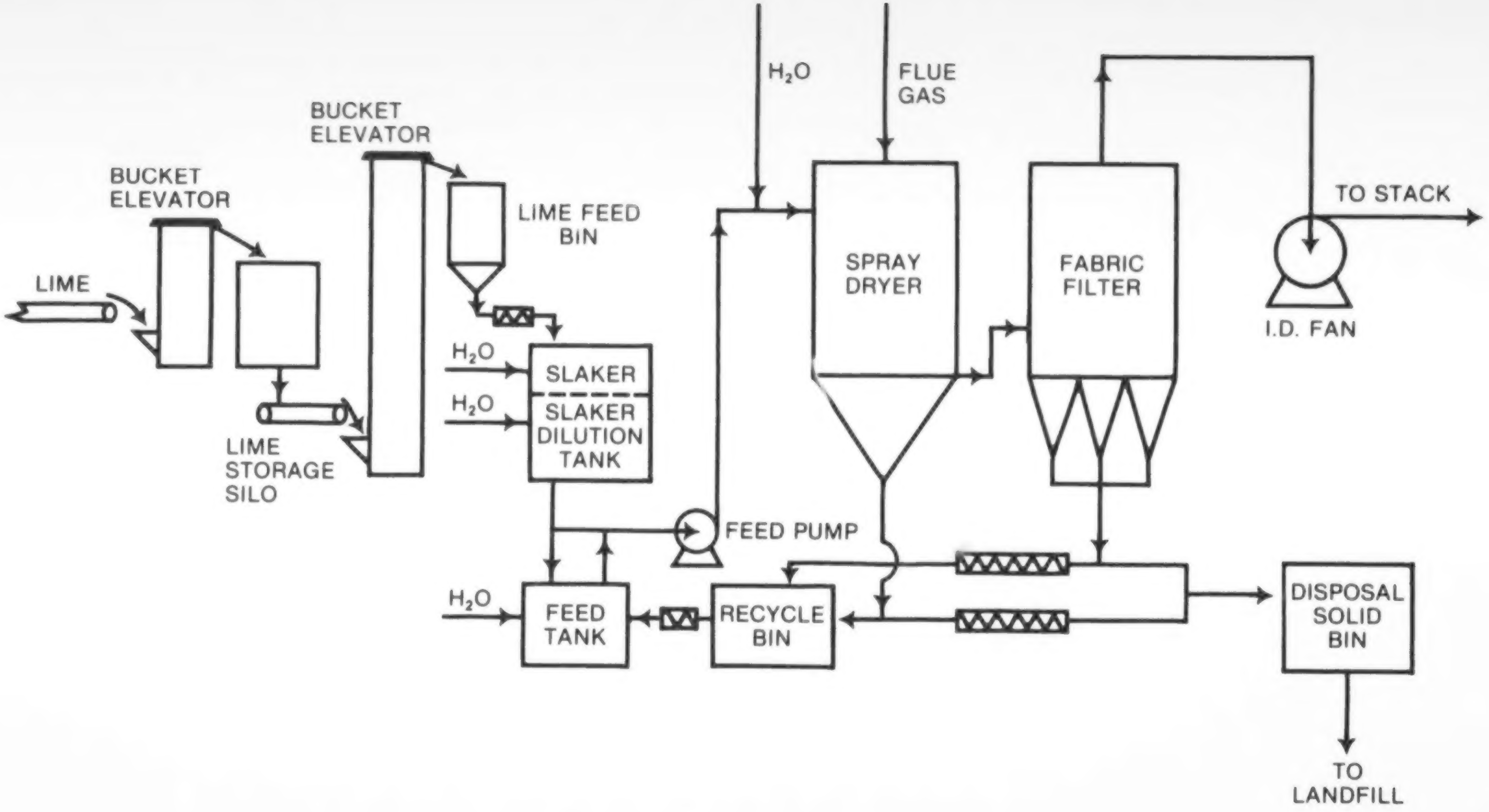

BUCKET ELEVATOR
BUCKET ELEVATOR
LIME
LIME STORAGE SILO
LIME FEED BIN
H_2O
SLAKER
H_2O
SLAKER DILUTION TANK
H_2O
FEED TANK
FEED PUMP
RECYCLE BIN
H_2O
FLUE GAS
SPRAY DRYER
FABRIC FILTER
TO STACK
I.D. FAN
DISPOSAL SOLID BIN
TO LANDFILL

Figure 11-1. Spray Dryer /Fabric Filter Process Flow Diagram.

TABLE 11.2 CRITERIA/ASSUMPTIONS FOR SPRAY DRYER/FABRIC FILTER SYSTEM DESIGN

1.	Spray Dryer Outlet Gas Temperature, °F	147
2.	Lime Purity, wt. percent CaO	96
3.	Spray Dryer Fresh Lime Feed Concentration, wt. percent	15
4.	Stoichiometric Ratio: (Values from Figure 5.2 with addition for fabric filter SO_2 removal)	

S.R.	% S	% SO_2 Removal
0.75	0.6	70
1.03	1.0	75
1.5	1.5	80

5.	Filter Bag Material	Teflon-coated Fiberglas
6.	Fabric Filter Inlet Gas Temperature, °F	147
7.	Air-to-Cloth Ratio, ft/min.	2
8.	Spray Dryer Gas Pressure Drop, in. H_2O	3
9.	Fabric Filter Gas Pressure Drop, in. H_2O	6
10.	Total System Gas Pressure Drop, in. H_2O	12
11.	FGD Waste Disposal	Landfill, deposited one mile from plant site.

TABLE 11.3 MAJOR EQUIPMENT LIST FOR SPRAY DRYER/FABRIC FILTER

(500 MW; 0.6% S Coal)

	Item	No.
1.	Lime Unloading Belt Conveyor	1
2.	Lime Storage Silo	1
3.	Lime Storage Silo Bucket Elevator	1
4.	Lime Feed Belt Conveyor	1
5.	Lime Feed Bucket Elevator	1
6.	Lime Feed Bin	2
7.	Slaker Feeder	2
8.	Slaker	2
9.	Slaker Dilution Tank with Agitator	2
10.	Slurry Feed Tank with Agitator	2
11.	Spray Dryer (4 operating, 1 spare)	5
12.	Spray Dryer Feed Pump (1 operating, 1 spare per dryer)	10
13.	Recycle Bin	2
14.	Recycle Bin Conveyor	2
15.	Spray Dryer Discharge Conveyor	5
16.	Fabric Filter	1
17.	Fabric Filter Discharge Conveyor	1
18.	Disposal Solids Bin	1
19.	I.D. Fans (3 operating, 1 spare)	4

WET FGD SYSTEMS - FABRIC FILTER/WET SCRUBBER AND ELECTROSTATIC PRECIPITATOR/ WET SCRUBBER

Process Description

One process flow diagram is presented in Figure 11-2 to represent the two wet FGD/particulate control systems evaluated in the technoeconomic study. The only major difference between the two systems is that a fabric filter is used in one system and an electrostatic precipitator is used in the other as the particulate removal device. The particulate control equipment in each case treats the incoming flue gas as the first step in the process. Materials handling, slurry preparation, gas handling, and waste disposal are also parts of the processes.

The flue gas enters the fabric filter or electrostatic precipitator for particulate removal and then proceeds to the wet FGD scrubber for SO_2 removal. The limestone scrubber is a simple spray tower, in which the flue gas is saturated in the quenching zone and SO_2 removal is completed in the SO_2 scrubbing zone. The saturated gas leaving the tower is mixed with by-passed flue gas for reheat before going to the stack. Most of the scrubber slurry is recycled to the feed tank and back to the scrubber, but a small fraction is sent directly to waste disposal.

Design Criteria and Assumptions

The system design criteria and assumptions are tabulated in Table 11.4 for the fabric filter/limestone scrubber system and in Table 11.5 for the electrostatic precipitator/limestone scrubber system. The major equipment items for the both systems are listed in Table 11.6.

TABLE 11.4 CRITERIA/ASSUMPTIONS FOR ELECTROSTATIC PRECIPITATOR/ LIMESTONE SCRUBBER SYSTEM DESIGN

1.	**Electrostatic Precipitator**	
	a. Type	Cold ESP
	b. Specific Collection Area, ft^3	

% S	SCA
0.6	880
1.0	685
1.5	443

	c. Gas Pressure Drop, in. H_2O	1
2.	**Limestone Scrubber**	
	a. Type	Single Loop Scrubber
	b. $CaCO_3$ Utilization, %	90 (average)
	c. Limestone Purity, wt.%	95
	d. Gas Pressure Drop, in. H_2O	4
3.	Total System Gas Pressure Drop, in. H_2O	9
4.	FGD Waste Disposal	Clay-lined pond, one mile from plant site.

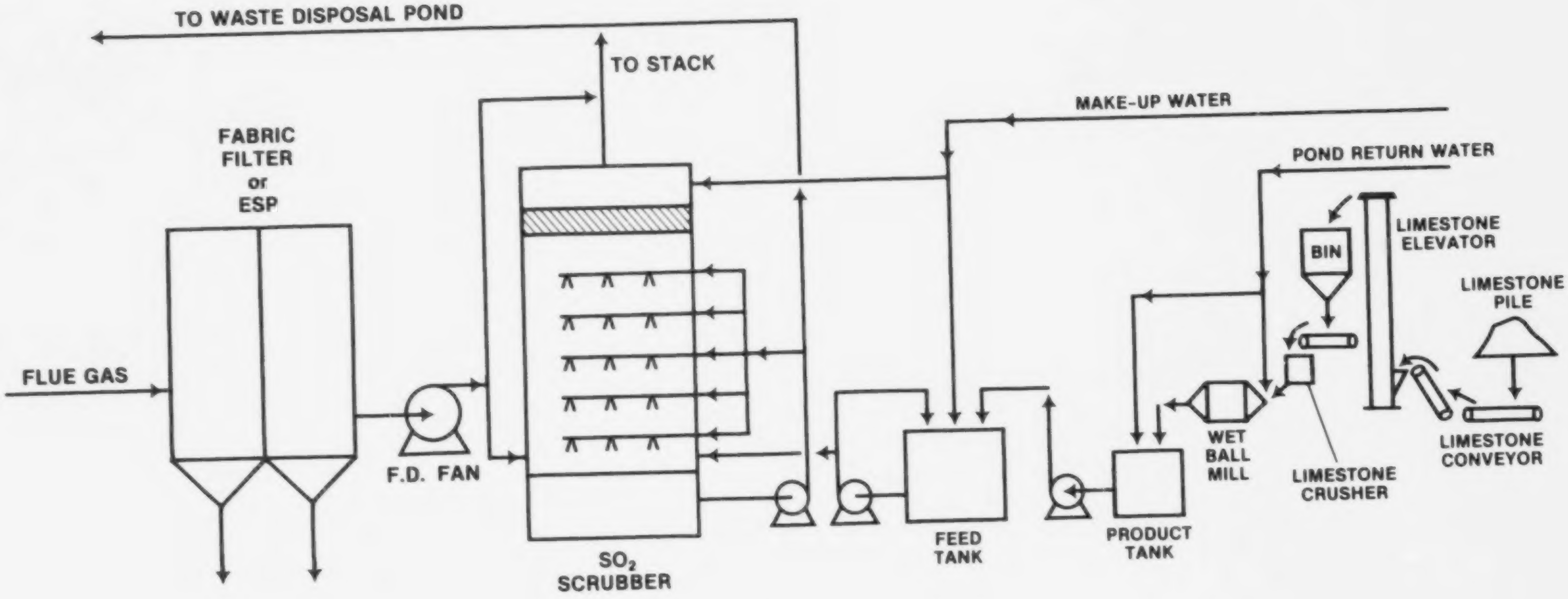

TO WASTE DISPOSAL POND
TO STACK
MAKE-UP WATER
POND RETURN WATER
FABRIC FILTER or ESP
FLUE GAS
F.D. FAN
SO_2 SCRUBBER
FEED TANK
PRODUCT TANK
WET BALL MILL
BIN
LIMESTONE ELEVATOR
LIMESTONE PILE
LIMESTONE CRUSHER
LIMESTONE CONVEYOR

Figure 11-2. Wet FGD Scrubber/Particulate Control Process Flow Diagram.

TABLE 11.5 CRITERIA/ASSUMPTIONS FOR FABRIC FILTER/ LIMESTONE SCRUBBER SYSTEM DESIGN

1.	Fabric Filter	
a.	Type	Reverse Air Baghouse
b.	Filter Bag Material	Teflon-coated Fiberglas
c.	Gas Pressure Drop, in. H_2O	6
2.	Limestone Scrubber	
a.	Type	Single Loop Scrubber
b.	$CaCO_3$ Utilization, %	90% (average)
c.	Limestone Purity, wt.%	95
d.	Gas Pressure Drop, in. H_2O	4
3.	Total System Gas Pressure Drop, in. H_2O	14
4.	FGD Waste Disposal	Clay-lined pond, one mile from plant site.

TABLE 11.6 MAJOR EQUIPMENT LIST FOR WET FGD LIMESTONE SCRUBBER
(500 MW, 0.6% S Coal)

	Item	No.
1.	Fabric Filter/Electrostatic Precipitator	1
2.	SO_2 Scrubber with Hot Gas Quencher	2
3.	Scrubber Feed Pump	8
4.	Slurry Feed Tank with Agitator	2
5.	Slurry Feed Tank Pump	4
6.	Ball Mill	1
7.	Ball Mill Product Tank with Agitator	1
8.	Ball Mill Product Tank Pump	4
9.	Limestone Crusher	1
10.	Crusher Feeder	1
11.	Crusher Feed Bin	1
12.	Limestone Feed Bucket Elevator	1
13.	Limestone Feed Belt Conveyor	1
14.	Limestone Feed Unloading Facilities	1
15.	F.D. Fan (3 operating, 1 spare)	4

ECONOMIC ANALYSIS

Economic Basis

The technoeconomic comparisons were based on estimates of capital and operating costs for the three SO_2/particulate control systems. Fixed capital costs include direct, indirect, and contingency costs. Other capital costs include charges such as allowance for system start-up and modification, interest for system construction, land, working capital, royalties, etc. and were estimated at 17 percent of fixed capital charges. The capital cost estimates for the spray dryer, fabric filter and electrostatic precipitator are based on Research-Cottrell cost estimate information. Capital cost estimates for the limestone scrubber are based on published values (11-1, 11-2). Operating costs, which include direct and indirect costs, are presented as first-year annual revenue requirements. Capital and operating costs estimates are calculated based on the first quarter, 1981 dollars.

The equipment included in each pollution control system was divided into six functional areas for cost estimating purposes. They are solids material handling, slurry feed preparation, gas handling, SO_2 absorption, particulate removal, and waste disposal. The direct cost of each area was estimated independently. The total direct investment for each system is the sum of the six process area direct costs. Indirect investment was assumed to be 30 percent of the total direct system investment. Contingency costs were taken to be 20 percent of the sum of direct and indirect costs.

Capital Cost Estimates

Comparison of the total capital investment costs for the three SO_2/particulate pollution control systems investigated indicates that the dry scrubbing system is less costly than the two wet FGD systems. Table 11.7 shows that the total capital investment for a 500 MW spray dryer/fabric filter system treating flue gas generated from 0.6 percent S coal is estimated at $42,300,000. The fabric filter/limestone scrubber system cost estimate is $59,046,000 and the ESP/limestone scrubber system cost estimate is $63,699,000.

These cost estimates show that dry system costs are 30-35 percent lower than wet FGD/particulate systems costs for low sulfur coal applications. Unit costs for the three systems at a 500 MW size are $84.6/kw for the spray dryer/fabric filter, $118.1/kw for the fabric filter/limestone scrubber and $127.4/kw for the ESP/limestone scrubber case.

As Table 11.7 indicates, dry scrubbing system direct capital costs are lower than those for the wet FGD/particulate systems in each of the major process areas except materials handling. Gas handling, SO_2 absorption and waste disposal are all significantly less costly for the dry system. For particulate control in the low sulfur coal case (0.6 percent S) of this study, an electrostatic precipitator is considerably more expensive than a fabric filter.

TABLE 11.7 COMPARISON OF SYSTEM TOTAL CAPITAL INVESTMENTS

(500 MW, 0.6% S Coal, 70% SO_2 Removal Efficiency, 99.7% Particulate Efficiency)

	Total Cost, 1000$ (1981$)		
Investment Area	Lime Spray Dryer/ Fabric Filter	Fabric Filter/ Limestone Scrubber	Electrostatic Precipitator/ Limestone Scrubber
Material Handling	3,391	800	800
Feed Preparation	850	1,100	1,100
Gas Handling	5,975	8,554	8,554
SO_2 Absorption	7,145	11,802	11,802
Particulate Removal	9,230	10,990	13,973
Waste Disposal	524	4,604	4,604
Total Direct Investment	27,115	37,850	40,833
Indirect Investment	8,135	11,355	12,250
Contingency	7,050	9,841	10,616
Total Fixed Investment	42,300	59,046	63,699
Unit Cost ($/kW)	84.6	118.1	127.4

Gas handling section costs are higher for the wet FGD systems because of the use of flue gas by-passing around the scrubber which requires additional ductwork, supports, dampers, expansion joints and a gas mixing device. Also, the F.D. fans for the wet systems are larger than the I.D. fans for the dry system since the former operate on a higher temperature flue gas. Complex piping and spray manifolds and the use of corrosion-resistant materials of construction in the wet FGD systems produce higher SO_2 absorption section costs than for the simpler spray dryers in which carbon steel is utilized.

The clay-lined pond assumed for wet FGD waste product disposal entails much more capital investment than landfill preparation costs for dry scrubbing waste disposal, $ 4.6 million vs. $0.5 million, according to Table 11.7. The same basis was used for wet FGD waste disposal cost estimates in an earlier TVA study (11-1). If an FGD sludge/fly ash blending process were used for waste treatment before disposal to eliminate the need for a clay-lined disposal site, blending process capital investment costs were estimated to closely approximate clay-lining costs. With either waste disposal approach, wet FGD system disposal costs would still be significantly greater than those for dry system waste disposal.

The conclusions on capital investment arrived at in the present study are similar to those presented in the TVA economic comparison (11-1). In each study, the total fixed capital investment for the dry scrubbing system is about 30 percent less than for an ESP/limestone scrubber system. However, the fixed capital investment figures developed in the present study are 15 to 20 percent less than the corresponding TVA estimates. A significant part of the difference arises because the capital investment estimates of the present study are based on actual first quarter, 1981 dollars while the TVA study uses projected mid-1982 dollars. In view of the ± 30 percent error range associated with study or preliminary estimates, the capital investment costs generated for the present and TVA evaluations agree fairly well.

Operating Cost Estimates

Annual operating costs (first-year annual revenues) were estimated for the three pollution control cases studied for a 500 MW power plant burning 0.6 wt. percent S coal and operating 7000 hr/yr. Cost comparisons presented in Table 11.8 show that dry scrubbing system operating costs are about 25-30 percent lower than wet FGD/particulate control systems costs under the conditions investigated. All operating cost items except for raw materials, or reagent, costs are less for the dry scrubber system. Reagent costs are much higher for dry scrubbing than for wet scrubbing primarily because of the large cost differential between lime and limestone, $70/ton vs. $8/ton. Essentially all of the operating cost difference between dry and wet scrubbing systems determined in the present study is attributable to capital investment-related items, maintenance and capital charges.

TABLE 11.8 COMPARISON OF SYSTEM ANNUAL OPERATING COSTS

(500 MW, 0.6% S Coal, 70% SO_2 Removal Efficiency, 99.7% Particulate Removal Efficiency, 7000 hr/yr. Operation)

	Total Cost, 1000$ (1981$)		
Item	Lime Spray Dryer Fabric Filter	Fabric Filter/ Limestone Scrubber	Electrostatic Precipitator/ Limestone Scrubber
Raw Materials	1,026	225	225
Electricity	1,820	2,282	2,487
Water	40	73	73
Maintenance	1,654	3,217	3,062
Operating Labor	649	774	749
Overhead	832	1,269	1,274
Administration	65	77	75
Capital Charges	6,345	8,857	9,555
Total Cost, 1000$	12,431	16,774	17,500
Unit Cost, mills/kWh	3.6	4.8	5.0

Annual operating cost breakdowns for the three systems are given in Tables 11.9, 11.10 and 11.11. Items included in the cost breakdowns are raw materials (lime or limestone reagent), electricity, water, maintenance (labor and materials), labor (operating and analytical), admininstration, overhead and capital charges. Annual quantities of reagent, electricity and water were calculated from material and energy balances. Maintenance costs are considered to be a given percentage of the system direct investment. The percentage varied from 6.1 percent for the spray dryer/fabric filter system to 7.5 percent for the ESP/limestone scrubber system to 8.5 percent for the fabric filter/limestone scrubber system.

The results of the present study and those of TVA (11-1) indicate that dry scrubbing annual operating costs are 25 to 30 percent less than ESP/limestone scrubber costs. Annual operating cost estimates generated in the present study are only 70 to 75 percent of those developed by TVA. Much of the annual operating cost difference is attributable to lower capital charges used in the present study compared to the TVA work. Lower operating labor hourly rates and costs assumed in the present study also account for some of the operating cost difference.

TABLE 11.9 ANNUAL OPERATING COSTS FOR LIME SPRAY DRYER/FABRIC FILTER

(500 MW, 0.6% S Coal, 7000 hr/yr Operation)[a]

Item	Annual Quantity	Unit Cost (1981$)	Annual Cost (1981$)
Lime, tons	14,657	70	1,025,990
Electricity, kWh	36,397,000	0.05	1,819,850
Water, 1000 gal.	198,161	0.2	39,632
Maintenance, 6.1% of Direct Investment[b]			1,654,015
Labor, manhours	54,080	12	648,960
Total Direct Costs			5,188,447
Overhead, 20% of Utilities, Maintenance and Labor			832,491
Administration, 10% of Labor Cost			64,896
Capital Charges, 15% of Capital Investment			6,345,045
Total Indirect Costs			7,242,432
Total Annual Costs, $	12,430,878		
Unit Cost, mills/kWh	3.6		

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[a] SO_2 Removal Efficiency = 70%; Particulate Removal Efficiency = 99.7%.

[b] Based on maintenance cost estimates for individual investment areas shown in Table 11.7.

TABLE 11.10 ANNUAL OPERATING COSTS FOR FABRIC FILTER/LIMESTONE SCRUBBER

(500 MW, 0.6% S Coal, 7000 hr/yr Operation)

Item	Annual Quantity	Unit Cost (1981$)	Annual Cost (1981$)
Limestone, tons	28,184	8	225,472
Electricity, kWh	45,632,000	0.05	2,281,600
Water, 1000 gal.	365,000	0.2	73,000
Maintenance, 8.5% of Direct Investment			3,217,250
Labor, manhours	64,480	12	773,760
Total Direct Costs			6,571,082
Overhead, 20% of Utilities, Maintenance and Labor			1,269,122
Administration, 10% of Labor			77,376
Capital Charges, 15% of Capital Investment			8,856,900
Total Indirect Costs			10,203,398
Total Annual Costs, $	16,774,480		
Unit Cost, mills/kWh	4.8		

TABLE 11.11 ANNUAL OPERATING COSTS FOR ELECTROSTATIC PRECIPITATOR/LIMESTONE SCRUBBER

(500 MW, 0.6% S Coal, 7000 hr/yr Operation)[a]

Item	Annual Quantity	Unit Cost (1981$)	Annual Cost (1981$)
Limestone, tons	28,184	8	225,472
Electricity, kWh	49,740,000	0.05	2,487,000
Water, 1000 gal.	365,000	0.2	73,000
Maintenance, 7.5% of Direct Investment			3,062,475
Labor, manhours	64,420	12	749,040
Total Direct Costs			6,596,987
Overhead, 20% of Utilities, Maintenance and Labor			1,274,303
Administration, 10% of Labor			74,904
Capital Charges, 15% of Capital Investment			9,554,850
Total Indirect Costs			10,904,057
Total Annual Costs, $	17,501,044		
Unit Cost, mills/kWh	5.0		

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[a] SO_2 Removal Efficiency = 70%; Particulate Removal Efficiency = 99.7%.

Capital Cost Sensistivity

The capital cost sensitivity of the three different FGD systems to system size (MW) and percent sulfur in the coal was calculated.* They show that the capital costs for all three systems are only moderately affected by system size with unit costs decreasing as system size increases. The unit cost sensitivity for each of the three systems is nearly equal. The results are presented in Figures 11-3, 11-4, and 11-5 for 0.6 percent, 1.0 percent, and 1.5 percent sulfur coals, respectively.

The effect of increasing the sulfur content of the coal fired from 0.6 to 1.5 wt. percent influences the ESP/limestone scrubber system least and the spray dryer/fabric filter system to the greatest extent, as shown in Figure 11-6. Unit capital costs decrease by 5 percent for the ESP/limestone scrubber system, but increase 12 percent for the FF/limestone scrubber system and by 18 percent for the spray dryer/fabric filter system as percent S in the coal increases from 0.6 to 1.5 percent.

Operating Cost Sensitivity

Unit operating costs for each of the three systems decrease slightly as system size is increased between 250 and 500 MW, as shown in Figures 11-7, 11-8, and 11-9. Operating cost sensitivities are comparable for the systems under consideration. Unit operating costs are most affected by size for the fabric filter/limestone scrubber system (Figure 11-9) and least affected for the spray dryer/fabric filter system (Figure 11-7).

Unit operating costs are significantly influenced by the sulfur content of the coal burned in the dry scrubbing systems because of the use of increased amounts of expensive lime reagent. Between 0.6 percent S and 1.5 percent S, unit operating costs increase by about 46 percent for the spray dryer/fabric filter systems, 16 percent for the fabric filter/limestone scrubber system and only 4 percent for the ESP/limestone scrubber system.

Lime Reagent Cost

The sensistivity of lime reagent costs to percent S in the coal and raw material price for the present study basis is shown in Figure 11-10. According to Figure 11-10, lime reagent costs are somewhat more sensitive to increases in the coal sulfur content than to raw material price. Lime costs increase from 5 to 7 times to meet the reagent requirements as coal sulfur increases from 0.6 to 1.5 wt. percent. In this coal sulfur range, lime reagent costs, at a price of $70/ton increase from less than 10 percent of the total operating costs at 0.6 percent to about 30 percent at 1.5 percent S. Since lime reagent cost is very sensitive to sulfur level, dry scrubbing enjoys its greatest economic advantage over wet FGD systems for low sulfur coal applications. As coal sulfur content increases, the cost difference between wet and dry systems decreases. The operating cost crossover range is about 1.5 to 1.8 sulfur coal for the bases used in the present study (Figure 11-11).

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*Sensitivity was determined using appropriate exponential factors (based on values used by Cottrell Environmental Sciences, Inc.) for each investment area shown in Table 11.7.

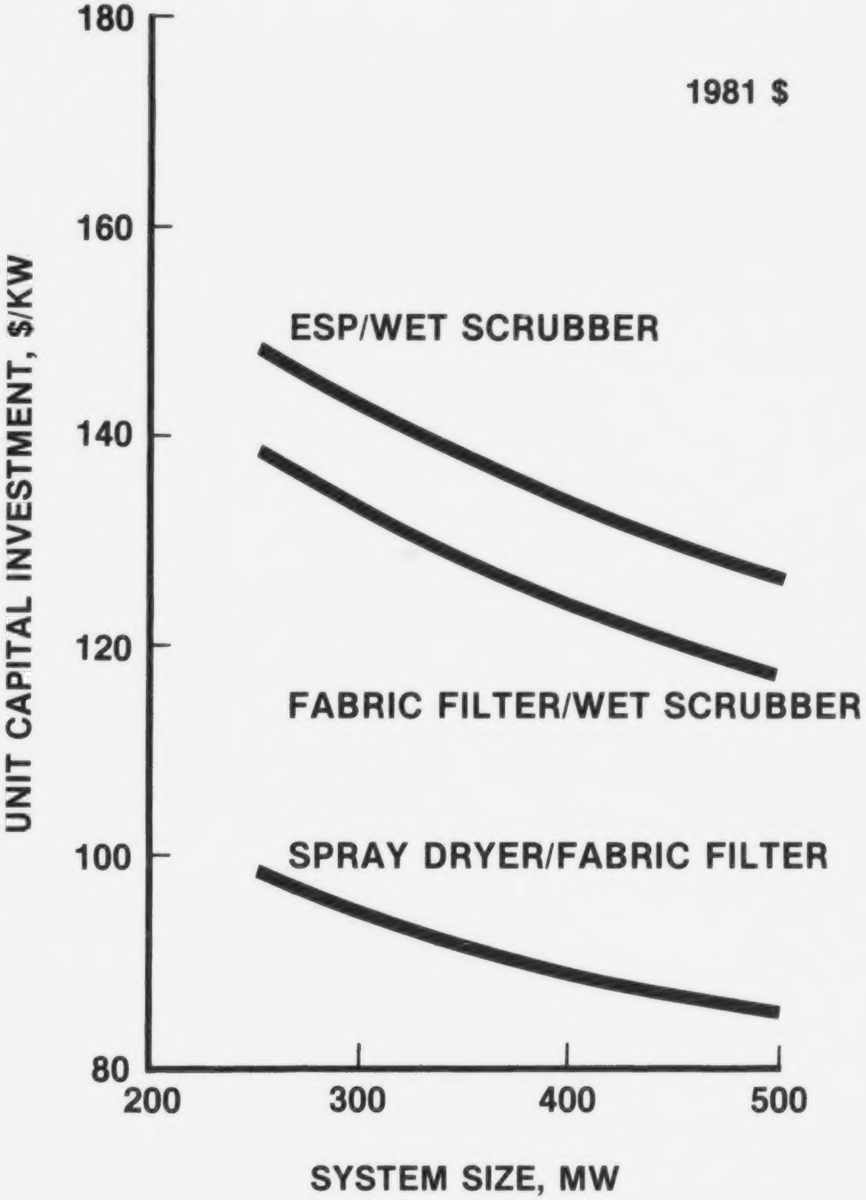

Figure 11-3. Capital Investment Comparison at 0.6 Wt.% Sulfur Coal.

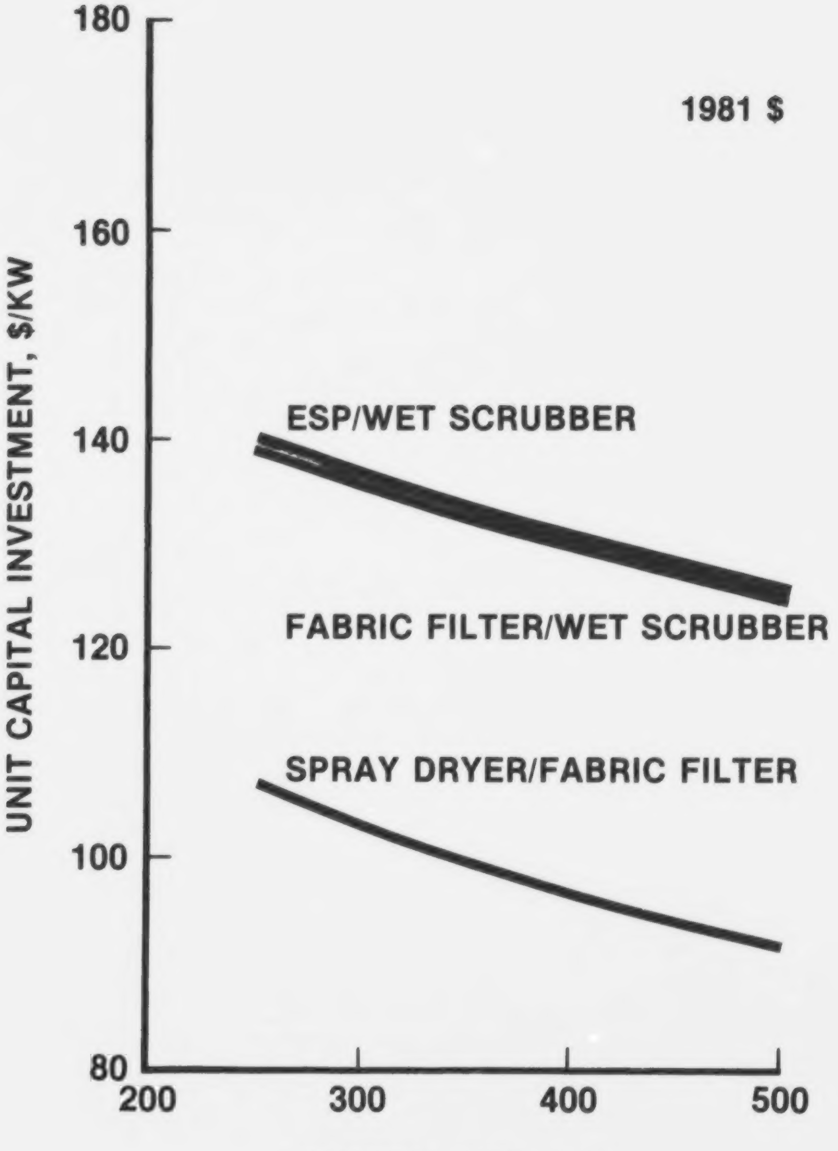

Figure 11-4. Capital Investment Comparison at 1.0 Wt.% Sulfur Coal.

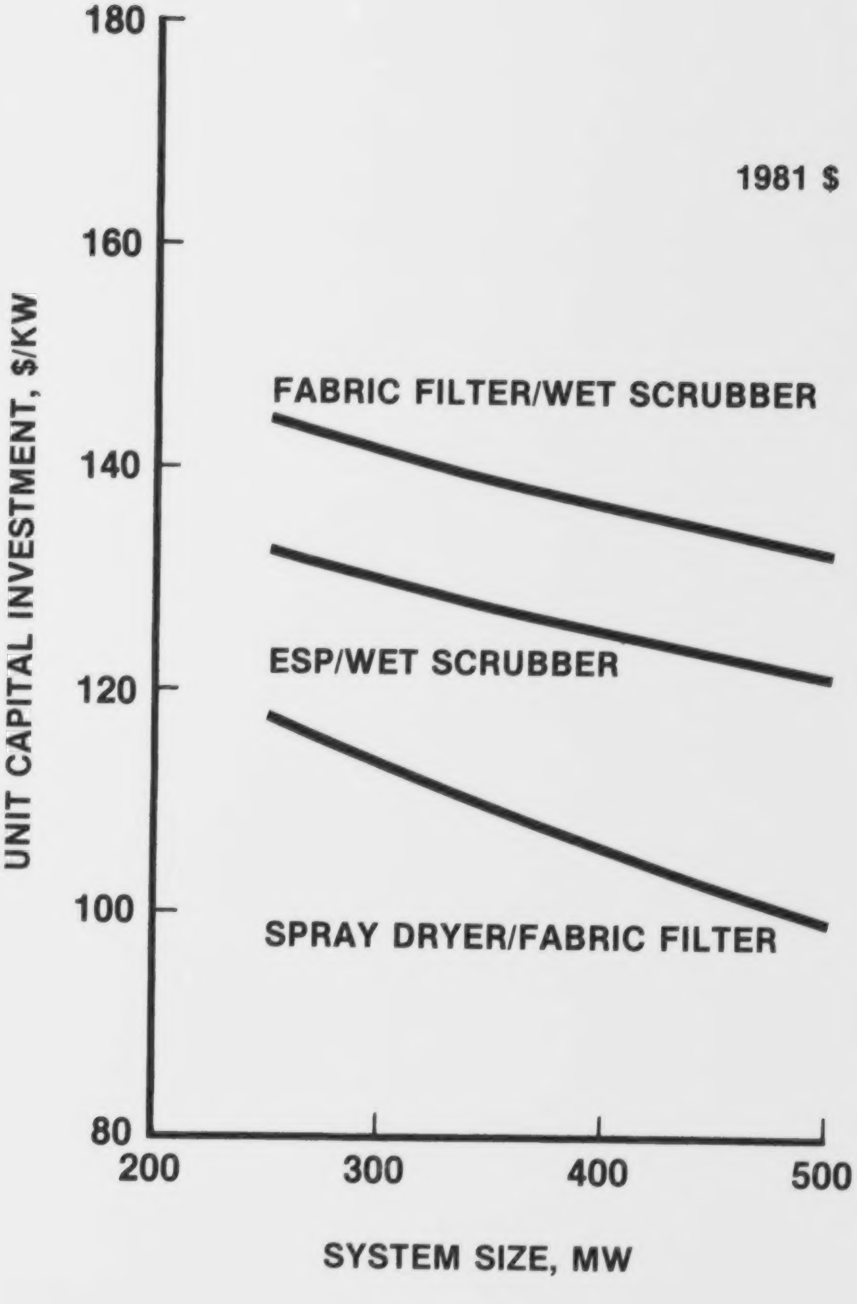

Figure 11-5. Capital Investment Comparison at 1.5 Wt.% Sulfur Coal.

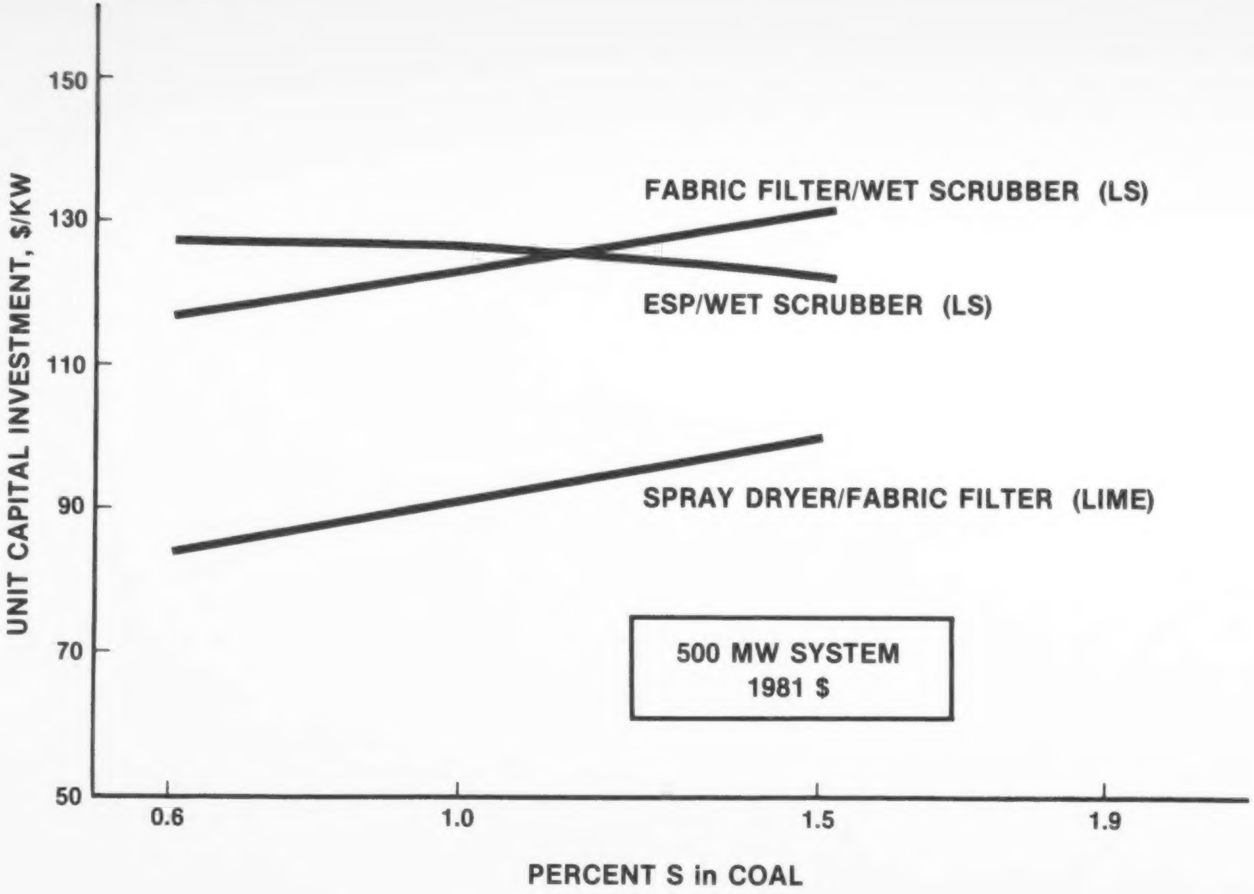

Figure 11-6. Unit Capital Investment Cost Sensitivity.

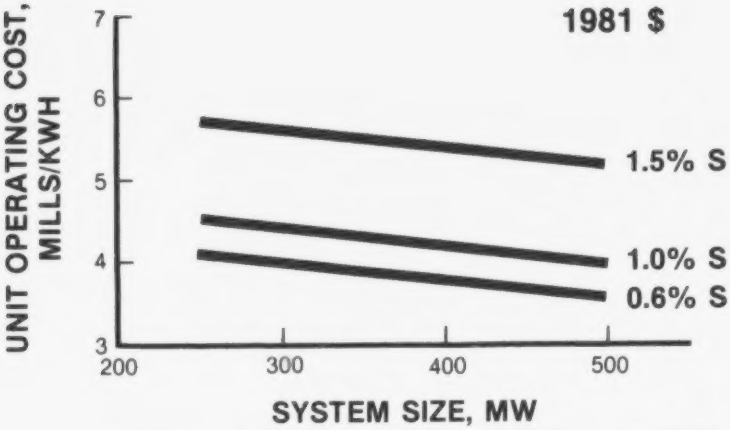

Figure 11-7. Spray Dryer/Fabric Filter Operating Cost Sensitivity.

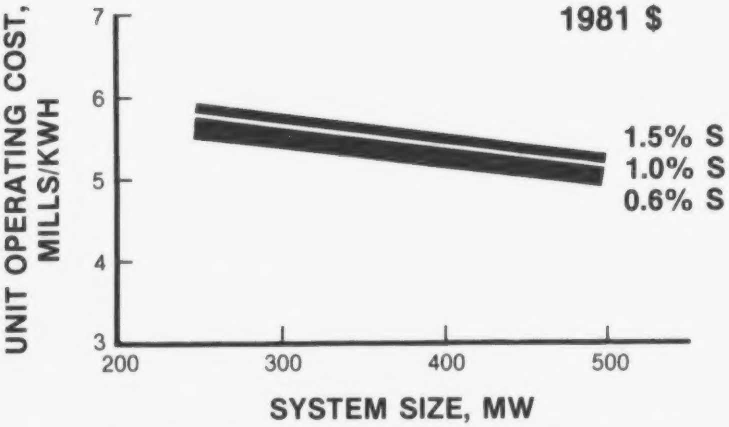

Figure 11-8. ESP/Wet FGD Scrubber Operating Cost Sensitivity.

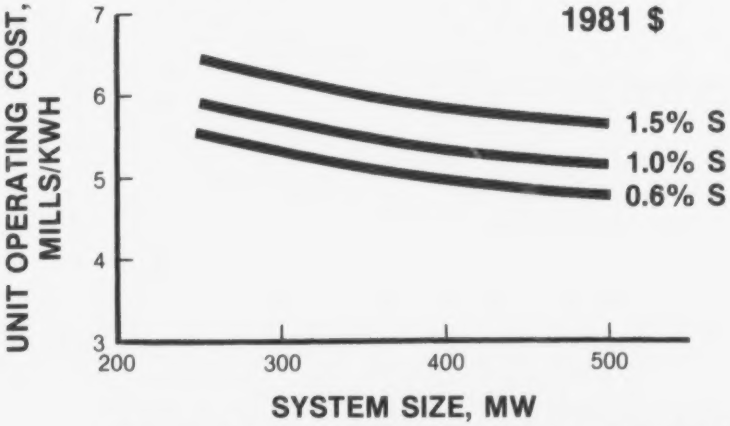

Figure 11-9. Fabric Filter/Wet FGD Scrubber Operating Cost Sensitivity.

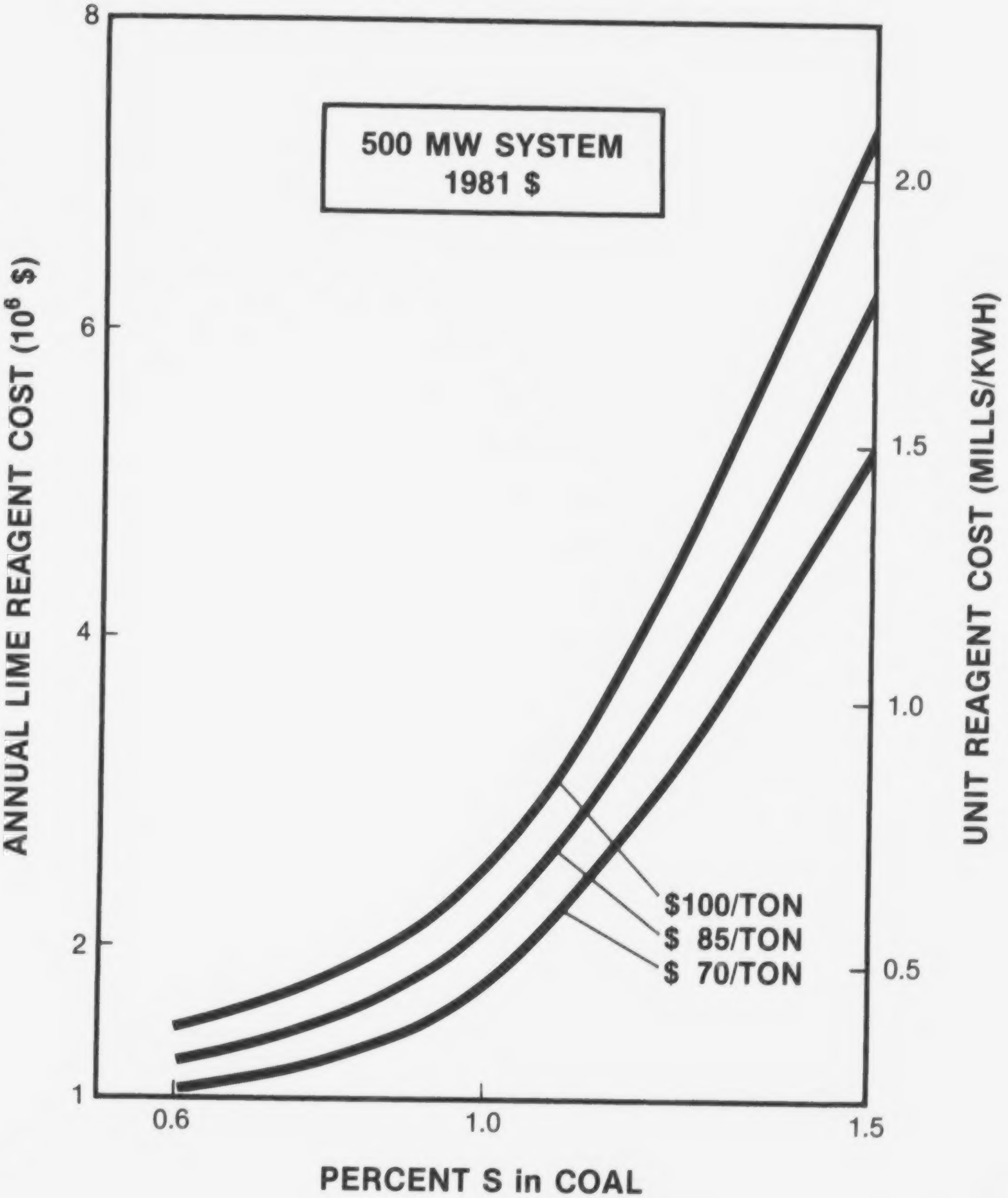

Figure 11-10. Lime Reagent Cost Sensitivity.

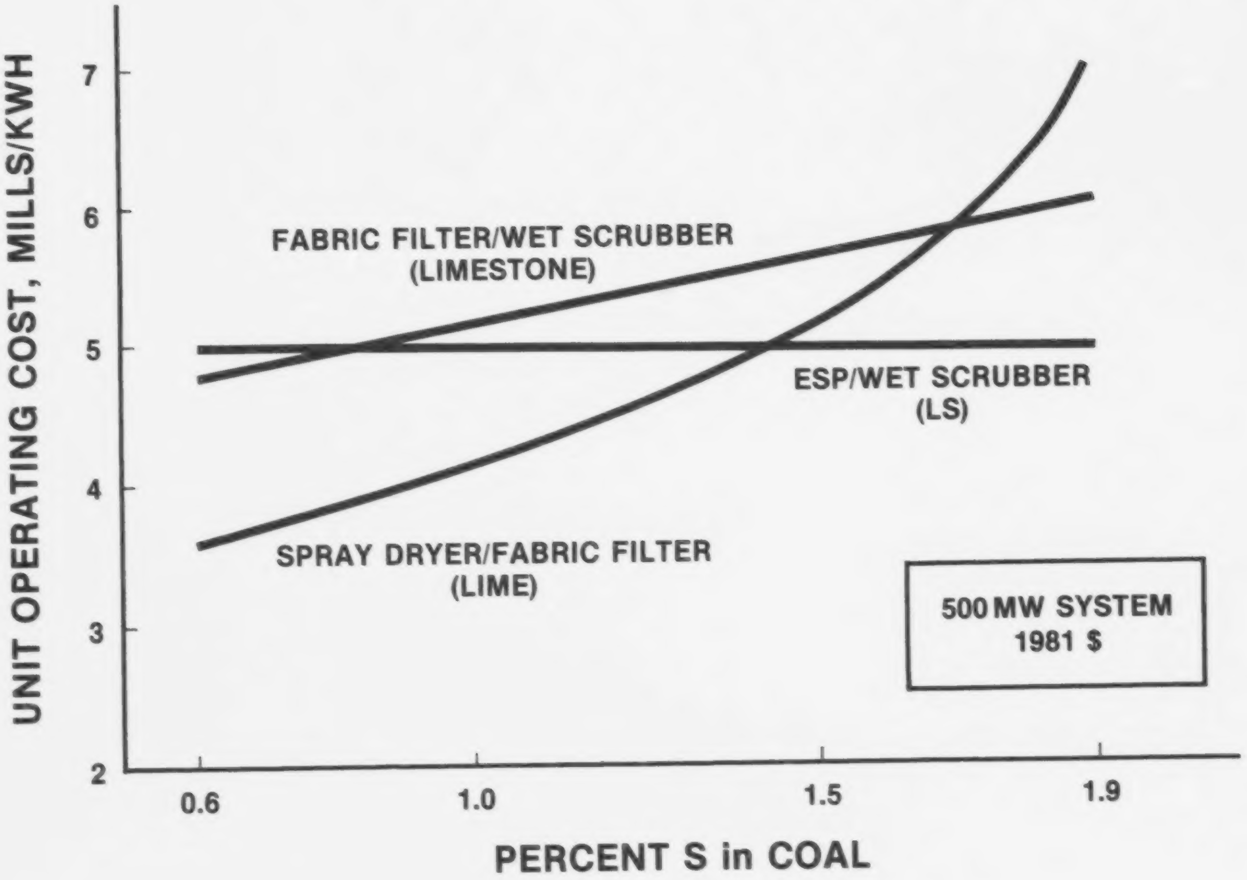

Figure 11-11. Unit Operating Cost Sensitivity.

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APPENDIX A

TABLE A.1. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
(NO.)	S.G.	SOLIDS (WT. PCT)	S.D.INLET (PPMV)	S.D.OUTLET (PPMV)	F.F.OUTLET (PPMV)	S.D.INLET (VOL. PCT)	S.D.OUTLET (VOL. PCT)	F.F.OUTLET (VOL. PCT)	S.D.OUTLET (DEG.F)	F.F.OUTLET (DEG.F)
101	0.0	0.0	780.	330.	135.	5.2	6.0	8.0	125.	120.
102	0.0	0.0	815.	320.	115.	5.2	6.0	8.0	125.	120.
103	0.0	0.0	770.	240.	30.	5.2	6.0	8.0	126.	120.
104	0.0	0.0	710.	165.	70.	5.2	6.0	8.0	125.	120.
105	0.0	0.0	780.	430.	270.	5.2	6.0	8.0	126.	120.
106R	0.0	0.0	800.	310.	105.	5.2	6.0	8.0	126.	120.
107	0.0	0.0	730.	320.	150.	5.2	6.0	8.0	126.	120.
108	0.0	0.0	675.	290.	205.	5.2	6.0	8.0	126.	120.
109	0.0	0.0	800.	440.	320.	5.2	6.0	8.0	126.	120.
110	0.0	0.0	800.	280.	120.	5.2	6.0	8.0	126.	120.
111	0.0	0.0	780.	270.	85.	5.2	6.0	8.0	126.	120.
112	0.0	0.0	750.	140.	50.	5.2	6.0	8.0	126.	120.
113	0.0	0.0	800.	360.	275.	5.2	6.0	8.0	126.	120.
114	0.0	0.0	780.	385.	175.	5.2	6.0	8.0	126.	120.
115	0.0	0.0	770.	300.	127.	5.2	6.0	8.0	126.	120.
116	0.0	0.0	800.	230.	115.	5.2	6.0	8.0	127.	120.
117	0.0	0.0	800.	330.	190.	5.2	6.0	8.0	126.	120.
118	0.0	0.0	810.	140.	60.	5.2	6.0	8.0	125.	120.
119	0.0	0.0	770.	250.	100.	5.2	6.0	8.0	125.	120.
120	0.0	0.0	790.	400.	270.	5.2	6.0	8.0	124.	120.
120R	0.0	0.0	900.	305.	160.	5.2	6.0	8.0	125.	120.
121	0.0	0.0	800.	350.	210.	5.2	6.0	8.0	126.	120.
123	0.0	0.0	810.	255.	210.	5.2	6.0	8.0	124.	120.
125	0.0	0.0	800.	290.	195.	5.2	6.0	8.0	126.	120.
126	0.0	0.0	800.	260.	140.	5.2	6.0	8.0	126.	120.

TABLE A.1. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
101	334.	194.	184.	137.	505.	0.65	0.67	1.13	18.9	0.0
102	335.	185.	175.	135.	520.	0.72	0.74	1.14	20.8	0.0
103	349.	167.	162.	130.	550.	0.78	0.74	1.14	20.8	0.0
104	340.	158.	156.	131.	555.	0.76	0.30	1.14	20.8	0.0
105	301.	200.	195.	146.	530.	0.79	0.52	1.13	19.2	0.0
106R	300.	177.	170.	138.	525.	0.81	0.70	1.13	19.2	0.0
107	300.	178.	173.	135.	555.	0.79	0.55	1.13	19.2	0.0
108	303.	184.	177.	138.	560.	0.82	0.48	1.13	19.2	0.0
109	307.	188.	180.	140.	550.	0.87	0.30	1.13	19.2	0.0
110	300.	161.	157.	134.	550.	0.84	0.30	1.14	20.2	0.0
111	301.	160.	156.	130.	560.	0.98	0.37	1.14	20.2	0.0
112	307.	148.	145.	129.	550.	0.79	0.37	1.12	17.1	0.0
113	261.	179.	175.	141.	560.	0.91	0.65	1.14	19.9	0.0
114	272.	173.	170.	143.	560.	0.90	0.89	1.14	19.9	0.0
115	256.	157.	152.	138.	570.	0.95	0.35	1.14	19.9	0.0
116	261.	142.	141.	131.	560.	0.93	0.30	1.14	19.9	0.0
117	339.	181.	175.	141.	550.	0.73	0.44	1.14	19.9	0.0
118	340.	140.	140.	127.	540.	0.66	0.30	1.12	17.5	0.0
119	340.	157.	152.	129.	545.	0.67	0.30	1.12	17.5	0.0
120	341.	185.	179.	142.	550.	0.66	0.30	1.12	17.5	0.0
120R	340.	181.	177.	149.	530.	0.73	0.76	1.12	17.5	0.0
121	334.	198.	192.	138.	550.	0.74	0.91	1.12	17.5	0.0
123	301.	164.	158.	142.	560.	0.80	0.30	1.07	10.5	0.0
125	262.	144.	142.	138.	570.	0.94	0.33	1.07	10.5	0.0
126	260.	144.	142.	131.	570.	0.92	0.46	1.07	10.5	0.0

TABLE A.1. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
101	5325.	4381.	3916.	3856.	4052.	10.5	2.0	71.3	0.0
102	5648.	4581.	4043.	3980.	4227.	10.2	2.1	87.7	0.0
103	5967.	4780.	4059.	4026.	4328.	10.2	2.1	87.7	0.0
104	5905.	4654.	3939.	3926.	4269.	10.5	2.1	35.6	0.0
105	5946.	4571.	4263.	4231.	4437.	5.7	2.2	56.3	0.0
106R	6005.	4634.	4198.	4152.	4467.	9.8	2.2	75.8	0.0
107	6020.	4508.	4090.	4058.	4323.	10.1	2.2	59.5	0.0
108	6149.	4600.	4193.	4147.	4412.	9.8	2.2	51.9	0.0
109	6302.	4786.	4367.	4313.	4583.	9.4	2.3	32.5	0.0
110	6193.	4669.	4131.	4104.	4478.	10.0	2.2	34.5	0.0
111	6722.	5015.	4435.	4406.	4783.	9.3	2.3	42.5	0.0
112	6006.	4561.	3940.	3921.	4326.	10.5	2.1	35.3	0.0
113	6477.	4579.	4346.	4318.	4632.	9.5	2.3	73.6	0.0
114	6442.	4623.	4298.	4277.	4640.	9.6	2.3	100.7	0.0
115	6651.	4623.	4283.	4248.	4705.	9.6	2.3	39.6	0.0
116	6548.	4629.	4174.	4167.	4644.	9.9	2.2	34.0	0.0
117	5773.	4567.	3992.	3955.	4242.	10.3	2.1	49.8	0.0
118	5462.	4370.	3605.	3605.	3997.	11.4	1.9	29.4	0.0
119	5517.	4392.	3712.	3682.	4016.	11.1	2.0	29.4	0.0
120	5489.	4353.	3818.	3783.	4039.	10.8	2.0	29.4	0.0
120R	5716.	4619.	4033.	4008.	4343.	10.2	2.1	74.5	0.0
121	5812.	4598.	4110.	4073.	4234.	10.0	2.2	89.2	0.0
123	6073.	4531.	4029.	3991.	4405.	10.2	2.1	16.8	0.0
125	6616.	4637.	4189.	4175.	4700.	9.8	2.2	18.5	0.0
126	6545.	4575.	4142.	4128.	4593.	10.0	2.2	25.7	0.0

TABLE A.1. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
101	0.0	18.9	8.7	4.0	54.1	53.6	78.7	3.26	24.
102	0.0	20.7	8.8	3.6	57.3	59.3	82.6	3.67	23.
103	0.0	20.0	6.8	1.0	65.9	85.8	95.2	3.79	25.
104	0.0	18.2	4.6	2.2	74.5	51.9	87.8	1.69	52.
105	0.0	20.6	12.2	8.7	40.7	28.8	57.8	2.36	25.
106R	0.0	21.4	9.0	3.4	58.1	61.6	83.9	3.05	28.
107	0.0	19.0	9.0	4.8	52.6	46.9	74.8	2.70	28.
108	0.0	17.9	8.3	6.7	53.6	19.9	62.8	2.51	25.
109	0.0	21.9	13.0	10.7	40.6	17.6	51.0	1.28	40.
110	0.0	21.6	8.2	4.0	62.0	51.4	81.6	1.38	59.
111	0.0	22.6	8.5	3.0	62.4	64.3	86.6	1.62	53.
112	0.0	19.6	4.0	1.6	79.7	59.5	91.8	1.55	59.
113	0.0	22.3	10.8	9.3	51.8	13.4	58.3	2.84	20.
114	0.0	21.7	11.5	5.9	46.9	48.5	72.7	4.02	18.
115	0.0	21.9	9.2	4.4	58.1	52.0	79.9	1.56	51.
116	0.0	22.6	7.0	4.0	68.9	43.3	82.4	1.30	63.
117	0.0	20.1	9.0	5.9	55.1	34.7	70.7	2.14	33.
118	0.0	19.5	3.7	1.8	81.0	51.4	90.8	1.31	70.
119	0.0	18.6	6.6	3.0	64.4	54.7	83.9	1.37	61.
120	0.0	18.9	10.4	8.0	44.9	23.5	57.8	1.35	43.
120R	0.0	20.3	8.4	5.0	58.4	40.5	75.3	3.17	24.
121	0.0	20.2	9.6	6.5	52.5	32.0	67.7	3.81	18.
123	0.0	21.2	7.2	6.8	65.9	6.7	68.1	0.68	***
125	0.0	22.6	8.5	6.7	62.2	21.1	70.2	0.71	99.
126	0.0	22.4	7.8	4.8	64.9	39.0	78.6	0.99	79.

TABLE A.2. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D. INLET	S.D. OUTLET	F.F. OUTLET	S.D. INLET	S.D. OUTLET	F.F. OUTLET	S.D. OUTLET	F.F. OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
129	0.0	0.0	840.	255.	140.	5.2	6.0	8.0	127.	120.
130	0.0	0.0	800.	210.	110.	5.2	6.0	8.0	125.	120.
131	0.0	0.0	800.	360.	210.	5.2	6.0	8.0	123.	120.
132	0.0	0.0	800.	325.	310.	5.2	6.0	8.0	125.	120.
133	0.0	0.0	780.	470.	385.	5.2	6.0	8.0	125.	120.
134	0.0	0.0	800.	560.	495.	5.2	6.0	8.0	125.	120.
201	0.0	0.0	1405.	640.	460.	5.2	6.0	8.0	119.	114.
202	0.0	0.0	1275.	525.	420.	3.0	3.5	5.0	117.	114.
202R	0.0	0.0	1452.	595.	368.	3.0	3.5	5.0	117.	114.
203	0.0	0.0	1400.	660.	540.	3.0	3.5	5.0	117.	114.
204	0.0	0.0	1487.	725.	470.	3.0	3.5	5.0	117.	114.
205	0.0	0.0	1450.	810.	600.	3.0	3.5	5.0	117.	114.
206	0.0	0.0	1465.	580.	350.	3.0	3.5	5.0	117.	114.
207R	0.0	0.0	1365.	660.	515.	3.0	3.5	5.0	117.	114.
212	0.0	0.0	1355.	445.	225.	3.0	3.5	5.0	117.	114.
213	0.0	0.0	1320.	640.	560.	3.5	5.0	6.0	117.	114.
214	0.0	0.0	1340.	530.	330.	3.0	3.5	5.0	117.	114.
215	0.0	0.0	1330.	286.	120.	3.0	3.5	5.0	117.	114.
216	0.0	0.0	1300.	400.	220.	3.5	4.5	6.0	117.	114.
217	0.0	0.0	1470.	810.	580.	3.5	4.5	6.0	117.	114.
218	0.0	0.0	1430.	1020.	920.	4.3	5.2	6.5	117.	114.
219	0.0	0.0	1320.	960.	780.	4.3	5.2	6.5	117.	114.
220	0.0	0.0	1350.	950.	755.	5.5	5.5	6.5	117.	114.
221	0.0	0.0	1290.	450.	205.	3.0	3.5	5.0	117.	114.
222	0.0	0.0	1430.	640.	440.	5.0	5.5	6.5	116.	114.

TABLE A.2 SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
129	342.	163.	158.	143.	560.	0.78	0.97	1.07	10.5	0.0
130	340.	145.	140.	137.	545.	0.71	0.48	1.07	10.5	0.0
131	342.	145.	140.	132.	550.	0.74	0.30	1.07	10.5	0.0
132	299.	176.	170.	152.	540.	0.81	0.86	1.07	10.5	0.0
133	298.	201.	195.	163.	525.	0.77	0.61	1.07	9.8	0.0
134	301.	222.	215.	183.	535.	0.75	0.63	1.09	13.7	0.0
201	300.	179.	175.	147.	550.	0.84	0.95	1.16	23.4	0.0
202	308.	172.	168.	145.	500.	0.70	0.51	1.10	13.4	0.0
202R	329.	164.	158.	144.	520.	0.71	2.40	1.10	13.4	0.0
203	342.	186.	183.	162.	545.	0.76	0.73	1.09	13.7	0.0
204	341.	187.	182.	155.	525.	0.81	0.70	1.19	25.5	0.0
205	298.	182.	178.	149.	540.	0.82	0.94	1.10	15.4	0.0
206	301.	179.	175.	155.	530.	0.77	0.70	1.19	25.5	0.0
207R	303.	185.	180.	158.	550.	0.77	0.29	1.19	25.5	0.0
212	261.	141.	139.	138.	540.	0.98	0.80	1.13	19.4	0.0
213	263.	164.	161.	145.	557.	0.92	0.45	1.12	17.5	0.0
214	262.	160.	156.	145.	545.	0.84	0.80	1.10	15.5	0.0
215	307.	142.	140.	136.	550.	0.85	1.14	1.11	17.0	0.0
216	301.	140.	139.	137.	525.	0.84	0.45	1.11	16.4	0.0
217	304.	138.	137.	132.	545.	0.86	0.30	1.11	16.2	0.0
218	261.	180.	176.	150.	540.	0.89	0.24	1.13	18.9	0.0
219	265.	183.	179.	154.	533.	0.84	0.42	1.13	18.9	0.0
220	268.	188.	180.	149.	550.	0.87	0.95	1.16	23.3	0.0
221	260.	153.	149.	141.	540.	0.84	0.93	1.11	17.9	0.0
222	340.	181.	178.	154.	542.	0.72	1.21	1.15	21.5	0.0

TABLE A.2 SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
129	5997.	4715.	4010.	3978.	4399.	10.3	2.1	54.3	0.0
130	5679.	4521.	3757.	3726.	4201.	11.0	2.0	26.9	0.0
131	5812.	4615.	3827.	3796.	4244.	10.8	2.0	16.8	0.0
132	6051.	4593.	4160.	4121.	4537.	9.9	2.2	48.1	0.0
133	5855.	4506.	4222.	4184.	4510.	9.8	2.2	32.1	0.0
134	5808.	4442.	4260.	4216.	4552.	9.7	2.2	47.1	0.0
201	6193.	4660.	4233.	4207.	4558.	9.7	2.2	129.6	0.0
202	5511.	4409.	3848.	3824.	4000.	10.7	2.0	37.6	0.0
202R	5638.	4515.	3812.	3776.	4007.	10.8	2.0	176.8	0.0
203	5876.	4689.	4024.	4005.	4207.	10.2	2.1	54.5	0.0
204	6005.	4884.	4201.	4169.	4335.	9.8	2.2	106.2	0.0
205	6088.	4615.	4127.	4101.	4250.	10.0	2.2	79.7	0.0
206	5870.	4512.	4006.	3981.	4186.	10.3	2.1	106.2	0.0
207R	5929.	4479.	4000.	3968.	4161.	10.3	2.1	44.0	0.0
212	6656.	4799.	4227.	4213.	4567.	9.8	2.2	87.7	0.0
213	6503.	4623.	4433.	4412.	4567.	9.3	2.3	44.2	0.0
214	6177.	4438.	4011.	3985.	4249.	10.3	2.1	68.1	0.0
215	6230.	4731.	3964.	3951.	4261.	10.4	2.1	107.8	0.0
216	6116.	4725.	4087.	4080.	4436.	10.1	2.2	41.0	0.0
217	6251.	4752.	4085.	4078.	4412.	10.1	2.2	27.0	0.0
218	6343.	4573.	4360.	4332.	4497.	9.5	2.3	25.6	0.0
219	6140.	4483.	4271.	4245.	4414.	9.7	2.3	44.8	0.0
220	6302.	4543.	4120.	4069.	4121.	10.0	2.2	128.9	0.0
221	6162.	4437.	3980.	3954.	4236.	10.4	2.1	87.9	0.0
222	5711.	4559.	3908.	3890.	3985.	10.5	2.1	149.6	0.0

TABLE A.2. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
129	0.0	21.7	7.2	4.5	66.8	37.8	79.3	2.16	37.
130	0.0	19.9	5.7	3.4	71.2	40.6	82.9	1.17	71.
131	0.0	20.2	10.0	6.6	50.5	33.9	67.3	0.72	94.
132	0.0	21.3	9.3	10.1	56.1	-8.1	52.5	1.95	27.
133	0.0	20.4	13.2	12.3	35.2	7.2	39.9	1.36	29.
134	0.0	20.5	15.4	15.4	25.1	-0.2	25.0	1.98	13.
201	0.0	37.9	18.6	15.2	50.8	18.5	59.9	2.96	20.
202	0.0	32.2	14.1	12.2	56.3	13.1	62.1	1.01	62.
202R	0.0	36.5	16.0	10.7	56.3	32.9	70.6	4.18	17.
203	0.0	36.0	18.1	16.1	49.8	11.2	55.4	1.31	42.
204	0.0	39.9	20.7	14.6	48.1	29.6	63.5	2.30	28.
205	0.0	38.8	22.9	18.4	41.0	19.6	52.6	1.77	30.
206	0.0	38.2	16.0	10.5	58.1	34.5	72.6	2.40	30.
207R	0.0	35.2	18.0	15.2	48.9	15.3	56.7	1.08	53.
212	0.0	39.7	13.8	7.6	65.3	45.1	80.9	1.91	42.
213	0.0	37.1	20.0	18.6	46.1	7.0	49.9	1.03	49.
214	0.0	36.2	15.1	10.2	58.4	32.4	71.9	1.62	44.
215	0.0	36.1	8.3	3.8	77.0	54.4	89.5	2.58	35.
216	0.0	35.5	12.0	7.2	66.2	40.0	79.7	1.00	80.
217	0.0	40.2	24.3	19.0	39.5	21.9	52.7	0.58	91.
218	0.0	39.9	30.6	29.8	23.4	2.4	25.2	0.56	45.
219	0.0	35.9	28.0	24.7	21.9	12.1	31.3	1.08	29.
220	0.0	37.0	26.6	22.5	28.3	15.4	39.3	3.01	13.
221	0.0	35.0	12.8	6.4	63.2	50.5	81.8	2.17	38.
222	0.0	35.8	17.2	12.6	52.1	26.8	65.0	3.61	18.

TABLE A.3. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
RUN (NO.)	S.G.	SOLIDS (WT. PCT)	S.D.INLET (PPMV)	S.D.OUTLET (PPMV)	F.F.OUTLET (PPMV)	S.D.INLET (VOL. PCT)	S.D.OUTLET (VOL. PCT)	F.F.OUTLET (VOL. PCT)	S.D.OUTLET (DEG.F)	F.F.OUTLET (DEG.F)
223	0.0	0.0	1420.	560.	340.	4.0	4.5	5.0	115.	114.
224	0.0	0.0	1400.	380.	140.	4.0	4.5	5.0	115.	114.
225	0.0	0.0	1360.	200.	10.	4.0	4.5	5.0	115.	114.
301	0.0	0.0	2050.	1350.	1050.	3.0	3.5	5.0	117.	114.
302	0.0	0.0	2120.	950.	510.	3.0	3.5	5.0	117.	114.
303	0.0	0.0	2000.	650.	300.	5.0	5.0	7.5	119.	114.
304	0.0	0.0	1812.	383.	137.	3.0	3.5	5.0	117.	114.
305	0.0	0.0	1870.	800.	500.	3.0	3.5	5.0	117.	114.
307	0.0	0.0	7000.	1200.	900.	4.3	5.0	6.5	117.	114.
308R	0.0	0.0	2000.	1300.	1200.	3.8	4.0	4.7	116.	114.
310	0.0	0.0	1850.	350.	50.	3.8	4.0	4.7	116.	114.
311	0.0	0.0	2075.	1000.	650.	4.0	4.5	5.0	115.	114.
312	0.0	0.0	2050.	600.	350.	4.0	4.5	5.0	115.	114.
313	0.0	0.0	2100.	1050.	800.	4.0	4.5	5.0	115.	114.
314	0.0	0.0	1900.	1250.	1100.	5.5	6.0	6.5	115.	114.
315	0.0	0.0	1925.	1100.	1000.	5.5	6.0	6.5	115.	114.
316	0.0	0.0	2100.	1250.	1100.	5.5	6.0	6.5	115.	114.
317	0.0	0.0	2150.	1100.	800.	5.5	6.0	6.5	115.	114.
318	0.0	0.0	2000.	1850.	1600.	5.5	6.0	6.5	115.	114.
319	0.0	0.0	1800.	950.	625.	5.0	5.5	6.5	116.	114.
325	0.0	0.0	1800.	715.	440.	3.0	3.5	5.0	117.	114.
401	0.0	0.0	785.	430.	340.	3.0	3.5	5.0	127.	124.
401R	0.0	0.0	850.	550.	420.	3.0	3.5	5.0	127.	124.
402	1.1	10.5	860.	440.	350.	3.0	3.5	5.0	127.	124.
403	1.1	14.7	750.	370.	270.	3.0	3.7	6.0	129.	124.

TABLE A.3. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
223	345.	155.	154.	137.	537.	0.71	0.45	1.17	24.2	0.0
224	343.	155.	153.	139.	547.	0.69	0.63	1.17	24.2	0.0
225	341.	150.	148.	137.	550.	0.69	1.40	1.17	24.2	0.0
301	304.	183.	178.	153.	545.	0.80	0.95	1.10	15.6	0.0
302	298.	141.	140.	139.	547.	0.78	2.55	1.04	6.4	0.0
303	302.	142.	141.	132.	554.	0.78	0.40	1.16	22.8	0.0
304	261.	142.	140.	134.	550.	0.92	0.77	1.16	22.8	0.0
305	259.	146.	145.	135.	550.	0.95	0.83	1.06	8.7	0.0
307	298.	174.	169.	152.	520.	0.65	0.92	1.13	19.2	0.0
308R	302.	184.	184.	152.	525.	0.77	0.45	1.15	21.3	0.0
310	305.	142.	140.	137.	532.	0.84	1.09	1.15	21.3	0.0
311	341.	161.	158.	136.	549.	0.67	0.45	1.17	24.2	0.0
312	341.	144.	142.	132.	540.	0.68	0.65	1.17	24.2	0.0
313	340.	145.	144.	130.	540.	0.86	0.30	1.16	22.4	0.0
314	264.	183.	179.	150.	495.	0.76	0.95	1.16	22.7	0.0
315	265.	174.	165.	151.	552.	0.87	0.95	1.15	21.6	0.0
316	267.	188.	186.	164.	520.	0.90	0.55	1.16	22.7	0.0
317	345.	185.	183.	152.	530.	0.72	1.36	1.17	23.7	0.0
318	346.	186.	184.	157.	542.	0.73	0.61	1.17	23.7	0.0
319	343.	181.	180.	154.	548.	0.70	1.21	1.15	21.5	0.0
325	260.	157.	156.	152.	552.	0.87	0.95	1.16	22.1	0.0
401	333.	175.	170.	145.	540.	0.70	0.32	1.08	13.5	0.0
401R	343.	182.	179.	160.	515.	0.73	0.21	1.10	22.0	0.0
402	343.	181.	176.	156.	555.	0.76	0.26	1.09	17.0	0.21
403	343.	182.	177.	152.	515.	0.76	0.26	1.09	17.0	0.30

TABLE A.3. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
223	5657.	4567.	3752.	3746.	3753.	11.0	2.0	63.6	0.0
224	5604.	4469.	3679.	3667.	3692.	11.2	1.9	89.1	0.0
225	5613.	4451.	3646.	3634.	3677.	11.3	1.9	198.0	0.0
301	6029.	4583.	4077.	4045.	4220.	10.1	2.1	82.0	0.0
302	5959.	4485.	3790.	3784.	4101.	10.9	2.0	85.4	0.0
303	5979.	4493.	3683.	3677.	4188.	11.2	2.0	53.1	0.0
304	6481.	4626.	4081.	4068.	4372.	10.1	2.2	102.3	0.0
305	6586.	4688.	4169.	4162.	4444.	9.9	2.2	38.2	0.0
307	5366.	4150.	3722.	3693.	3930.	11.1	2.0	99.8	0.0
308R	5855.	4530.	3980.	3980.	3938.	10.4	2.1	55.1	0.0
310	6137.	4733.	3912.	3899.	4035.	10.5	2.1	133.5	0.0
311	5528.	4388.	3650.	3633.	3610.	11.3	1.9	63.6	0.0
312	5544.	4441.	3607.	3595.	3642.	11.4	1.9	91.9	0.0
313	6235.	4988.	4061.	4054.	4080.	10.2	2.2	38.9	0.0
314	5728.	4342.	4057.	4031.	3977.	10.2	2.1	125.2	0.0
315	6309.	4520.	4167.	4108.	4150.	9.9	2.2	118.0	0.0
316	6314.	4684.	4390.	4376.	4368.	9.4	2.3	72.4	0.0
317	5676.	4616.	3961.	3949.	3884.	10.4	2.1	188.8	0.0
318	5750.	4625.	3971.	3958.	3919.	10.4	2.1	84.7	0.0
319	5648.	4499.	3845.	3839.	3920.	10.7	2.0	149.6	0.0
325	6309.	4488.	4049.	4042.	4360.	10.2	2.1	121.6	0.0
401	5511.	4553.	3886.	3855.	4020.	10.6	2.0	23.3	0.0
401R	5677.	4672.	3984.	3965.	4177.	10.3	2.1	25.4	0.0
402	5905.	4672.	3979.	3948.	4151.	10.4	2.1	24.0	11.7
403	5788.	4767.	4109.	4077.	4438.	10.0	2.2	24.0	24.0

TABLE A.3. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
223	0.0	35.4	15.0	9.4	57.6	37.4	73.5	1.55	47.
224	0.0	34.3	10.0	3.8	70.8	62.0	88.9	2.25	40.
225	0.0	33.2	5.3	0.3	84.2	94.8	99.2	5.14	19.
301	0.0	54.1	37.6	31.8	30.4	15.6	41.2	1.31	31.
302	0.0	55.2	26.3	15.4	52.2	41.7	72.2	1.34	54.
303	0.0	51.9	17.5	9.3	66.3	46.6	82.0	0.89	93.
304	0.0	51.1	11.4	4.4	77.7	61.2	91.3	1.73	53.
305	0.0	53.6	24.2	16.4	54.9	32.1	69.4	0.62	***
307	0.0	48.2	31.0	25.4	35.7	18.0	47.2	1.79	26.
308R	0.0	52.3	35.3	34.0	32.4	3.9	35.1	0.91	38.
310	0.0	50.3	10.0	1.5	80.1	85.1	97.0	2.29	42.
311	0.0	50.0	25.8	17.3	48.3	33.0	65.4	1.10	59.
312	0.0	50.0	15.8	9.5	68.5	39.9	81.1	1.59	51.
313	0.0	57.6	31.0	24.3	46.2	21.5	57.7	0.58	99.
314	0.0	50.1	34.7	31.5	30.8	9.1	37.1	2.16	17.
315	0.0	52.8	31.8	29.9	39.8	6.1	43.4	1.93	22.
316	0.0	59.5	37.2	33.9	37.4	9.1	43.1	1.05	41.
317	0.0	54.2	29.7	22.3	45.2	24.8	58.8	3.01	20.
318	0.0	50.5	50.0	44.7	0.9	10.6	11.5	1.45	8.
319	0.0	44.3	25.1	17.5	43.5	30.0	60.4	2.91	21.
325	0.0	49.3	20.6	13.8	58.2	33.2	72.1	2.13	34.
401	0.0	19.8	11.6	9.9	41.6	14.2	49.9	1.02	49.
401R	0.0	21.7	15.0	12.4	31.0	17.1	42.8	1.01	42.
402	0.5	22.0	12.0	10.4	45.4	13.6	52.9	0.94	56.
403	1.0	19.6	10.4	8.6	46.6	17.3	56.0	1.06	53.

TABLE A.4. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
404	1.2	28.0	815.	422.	315.	3.0	3.5	5.0	127.	124.
405	1.2	28.0	800.	365.	290.	4.7	5.4	7.5	129.	124.
40R1	1.1	22.5	850.	400.	310.	2.5	3.6	5.1	127.	124.
40R2	1.2	25.5	760.	320.	240.	3.0	4.0	7.0	130.	124.
405A	1.2	25.5	430.	180.	140.	3.0	3.5	5.0	127.	124.
405B	1.3	35.0	740.	310.	230.	3.0	4.0	5.5	129.	125.
405C	1.3	40.0	1400.	700.	560.	3.0	3.5	5.0	127.	124.
405D	1.5	52.0	1875.	825.	660.	3.0	4.0	7.0	130.	124.
406	0.0	0.0	740.	355.	240.	3.0	3.5	5.0	127.	124.
407	1.1	14.7	800.	370.	250.	2.5	3.5	6.0	129.	124.
408	1.2	28.0	870.	380.	220.	3.0	3.5	5.0	127.	124.
409	1.2	30.0	850.	320.	170.	3.8	4.6	7.0	129.	124.
410	1.3	32.4	810.	275.	130.	3.0	3.5	5.0	127.	124.
411	0.0	0.0	790.	420.	340.	4.5	5.5	7.0	128.	124.
412	1.0	4.8	700.	300.	240.	3.3	4.7	7.0	129.	124.
413	1.1	19.0	880.	510.	410.	3.5	4.0	5.7	128.	124.
414	1.1	24.0	770.	370.	270.	5.5	6.0	8.0	129.	124.
415	1.2	29.5	740.	290.	210.	3.5	4.0	6.0	128.	124.
416	1.2	31.0	830.	370.	220.	2.6	3.0	4.1	128.	126.
417	1.2	31.0	780.	265.	180.	3.0	4.0	7.0	130.	124.
418	1.3	32.4	780.	250.	100.	5.0	5.5	7.5	130.	127.
419	1.3	32.4	785.	200.	40.	5.0	5.5	8.0	129.	124.
420	1.2	21.6	840.	440.	370.	4.5	5.5	7.0	128.	124.
421	1.1	24.5	820.	390.	310.	4.5	5.5	7.0	128.	124.
422	1.1	24.5	810.	300.	200.	3.5	4.0	6.0	128.	124.

TABLE A.4. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
RUN (NO.)	INLET (DEG.F)	OUTLET (DEG.F)	INLET (DEG.F)	OUTLET (DEG.F)	INLET (DEG.F)	INITIAL ΔP (IN. WATER)	FLOW (GPM)	S.G.	$C_A(OH)_2$ (WT. PCT)	FLOW (GPM)
404	341.	186.	179.	153.	520.	0.70	0.29	1.08	13.5	0.30
405	339.	187.	177.	162.	555.	0.73	0.29	1.08	13.5	0.40
40R1	339.	186.	180.	147.	510.	0.67	0.21	1.10	20.7	0.56
40R2	340.	180.	177.	152.	540.	0.73	0.36	1.06	12.5	0.36
405A	343.	177.	172.	155.	530.	0.73	0.21	1.06	12.5	0.26
405B	337.	178.	172.	149.	500.	0.74	0.23	1.12	18.7	0.34
405C	342.	182.	179.	166.	535.	0.71	0.41	1.12	18.7	0.48
405D	345.	185.	184.	165.	540.	0.70	0.58	1.12	18.7	0.48
406	334.	178.	173.	146.	495.	0.72	0.64	1.08	13.5	0.0
407	343.	182.	178.	150.	510.	0.76	0.52	1.09	16.7	0.30
408	352.	196.	190.	171.	555.	0.74	0.61	1.08	13.5	0.30
409	334.	174.	170.	153.	515.	0.73	0.51	1.09	16.7	0.53
410	344.	182.	176.	148.	535.	0.70	0.37	1.15	21.6	0.70
411	341.	183.	179.	161.	530.	0.71	0.23	1.11	19.1	0.0
412	343.	184.	179.	159.	545.	0.68	0.23	1.11	18.0	0.44
413	344.	184.	180.	153.	530.	0.68	0.23	1.11	18.0	0.25
414	342.	180.	176.	148.	510.	0.70	0.23	1.11	18.0	0.35
415	341.	184.	178.	157.	525.	0.73	0.23	1.11	19.1	0.41
416	339.	162.	160.	142.	520.	0.72	0.22	1.09	14.7	0.30
417	340.	163.	160.	143.	520.	0.73	0.25	1.09	14.7	0.35
418	343.	163.	160.	151.	550.	0.70	0.23	1.12	18.3	0.32
419	342.	161.	158.	141.	530.	0.73	0.28	1.12	18.3	0.70
420	259.	173.	170.	150.	520.	0.92	0.27	1.13	21.6	0.43
421	254.	171.	168.	156.	555.	0.90	0.63	1.05	7.5	0.63
422	268.	169.	165.	156.	550.	0.90	0.76	1.05	7.5	0.76

TABLE A.4. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE							SLURRY FEED RATE	
RUN (NO.)	ENTER COOLER (ACFM)	ENTER S.D. (ACFM)	EXIT S.D. (ACFM)	ENTER F.F. (ACFM)	EXIT F.F. (ACFM)	SPRAY DRYER RESIDENCE TIME (SEC)	FABRIC FILTER AIR-TO-CLOTH RATIO (FT/MIN)	LIME (LB/HR)	RECYCLE (LB/HR)
404	5569.	4551.	3910.	3868.	4028.	10.5	2.1	21.1	49.1
405	5787.	4556.	3985.	3923.	4347.	10.3	2.1	21.1	65.5
40R1	5420.	4465.	3962.	3925.	4044.	10.4	2.1	23.9	71.8
40R2	5744.	4596.	4027.	4008.	4530.	10.2	2.1	23.8	54.2
405A	5716.	4636.	3927.	3896.	4117.	10.5	2.1	13.9	39.1
405B	5667.	4705.	4124.	4085.	4284.	10.0	2.2	24.0	75.6
405C	5651.	4555.	3888.	3870.	4116.	10.6	2.1	42.9	128.3
405D	5625.	4528.	3974.	3968.	4530.	10.4	2.1	60.6	181.6
406	5575.	4635.	3968.	3937.	4092.	10.4	2.1	46.7	0.0
407	5773.	4779.	4180.	4154.	4539.	9.9	2.2	47.3	24.0
408	5827.	4661.	4012.	3976.	4190.	10.3	2.1	44.5	49.0
409	5672.	4619.	4005.	3980.	4439.	10.3	2.1	46.4	94.0
410	5611.	4534.	3863.	3827.	3972.	10.7	2.0	45.7	143.5
411	5637.	4561.	4027.	4002.	4266.	10.2	2.1	24.4	0.0
412	5558.	4441.	3987.	3956.	4373.	10.3	2.1	23.0	11.0
413	5516.	4480.	3830.	3806.	4010.	10.8	2.0	23.0	26.2
414	5540.	4581.	3917.	3892.	4217.	10.5	2.1	23.0	47.8
415	5701.	4636.	3975.	3938.	4257.	10.4	2.1	24.4	73.0
416	5648.	4605.	3815.	3802.	3918.	10.8	2.0	17.7	57.5
417	5687.	4642.	3975.	3956.	4526.	10.4	2.1	20.1	67.1
418	5653.	4495.	3748.	3730.	4150.	11.0	2.0	23.6	65.6
419	5716.	4630.	3855.	3836.	4332.	10.7	2.0	28.7	143.5
420	6384.	4684.	4462.	4441.	4716.	9.2	2.4	32.8	56.9
421	6426.	4520.	4320.	4299.	4625.	9.5	2.3	24.6	88.1
422	6410.	4620.	4202.	4175.	4559.	9.8	2.2	29.7	106.3

TABLE A.4. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
404	2.3	20.4	11.2	9.1	44.8	19.0	55.3	0.90	62.
405	3.1	20.1	9.9	8.9	50.7	9.9	55.6	0.91	61.
40R1	3.0	20.9	10.8	9.1	48.4	15.8	56.5	0.99	57.
40R2	2.3	19.2	8.9	7.8	53.9	11.8	59.3	1.07	55.
405A	2.8	10.9	4.9	4.1	55.3	15.6	62.3	1.10	57.
405B	3.1	19.2	8.8	7.1	54.1	19.3	63.0	1.08	58.
405C	3.0	35.0	18.6	16.2	46.7	13.1	53.7	1.06	51.
405D	3.0	46.4	22.3	21.0	51.8	5.9	54.6	1.13	48.
406	0.0	19.0	9.7	7.1	48.9	26.6	62.5	2.12	29.
407	0.5	20.9	10.6	8.2	49.4	22.8	60.9	1.95	31.
408	1.1	22.0	10.2	6.4	53.5	37.1	70.7	1.75	40.
409	2.0	21.7	8.9	5.4	59.1	39.1	75.1	1.84	41.
410	3.1	20.1	7.3	3.7	63.8	48.7	81.4	1.97	41.
411	0.0	19.8	11.6	10.3	41.5	11.2	48.1	1.06	45.
412	0.5	17.0	8.2	7.5	52.0	8.7	56.2	1.17	48.
413	1.1	21.6	13.3	11.8	38.1	11.6	45.3	0.92	49.
414	2.1	19.3	10.0	8.2	48.5	17.3	57.4	1.03	56.
415	3.0	18.8	7.9	6.4	58.2	19.1	66.2	1.12	59.
416	3.3	21.0	10.0	6.3	52.6	36.9	70.1	0.73	96.
417	3.3	19.9	7.4	5.9	62.6	20.1	70.2	0.87	80.
418	2.8	19.2	6.6	3.0	65.5	54.8	84.4	1.06	80.
419	5.0	19.9	5.5	1.3	72.6	76.8	93.6	1.25	75.
420	1.7	24.1	13.6	12.6	43.3	7.8	47.7	1.18	40.
421	3.6	22.8	11.7	10.2	48.6	12.8	55.2	0.93	59.
422	3.6	22.6	8.8	6.6	61.0	25.5	71.0	1.13	63.

TABLE A.5. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS.	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
423	1.4	50.4	810.	460.	310.	3.5	4.0	6.0	128.	124.
424	1.2	31.0	820.	420.	320.	5.0	5.5	7.5	128.	124.
425	1.2	31.0	810.	385.	250.	4.0	5.0	7.0	128.	124.
426	1.4	50.4	810.	270.	120.	3.5	4.0	5.0	127.	124.
427	1.2	31.0	810.	500.	370.	5.0	5.5	7.0	127.	123.
428	1.2	33.4	790.	310.	210.	5.3	5.6	6.9	127.	124.
429	1.2	33.4	760.	320.	180.	3.5	4.0	5.0	127.	124.
430	1.2	31.0	760.	270.	150.	4.3	5.8	6.7	127.	124.
432	0.0	0.0	810.	480.	340.	3.0	3.5	5.0	127.	124.
433	1.1	22.5	850.	340.	240.	3.5	4.0	5.5	127.	124.
434	1.1	22.5	770.	270.	190.	3.0	4.0	5.5	125.	120.
441A	1.2	31.0	810.	390.	280.	4.0	5.5	7.0	128.	124.
441B	1.2	31.0	800.	330.	180.	4.0	5.5	7.0	128.	124.
441C	1.2	31.0	780.	380.	200.	4.0	5.5	7.0	128.	124.
441D	0.0	0.0	760.	380.	320.	4.0	5.5	7.0	128.	124.
501	0.0	0.0	780.	340.	260.	5.1	6.7	7.5	128.	127.
501R	0.0	0.0	805.	400.	300.	5.0	5.5	7.5	130.	126.
502	0.0	0.0	800.	410.	330.	5.5	6.0	8.0	124.	118.
503	0.0	0.0	765.	400.	315.	5.0	5.5	7.0	122.	118.
503R	0.0	0.0	780.	420.	310.	5.0	5.5	7.0	129.	126.
504	0.0	0.0	810.	400.	310.	4.5	5.5	7.5	130.	128.
504R	0.0	0.0	775.	395.	270.	4.5	5.5	7.5	130.	127.
505	0.0	0.0	740.	320.	170.	5.0	6.5	7.8	129.	126.
505R	0.0	0.0	745.	285.	165.	5.0	6.0	8.0	130.	126.
506	0.0	0.0	850.	510.	340.	5.0	6.0	8.0	130.	127.

TABLE A.5. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY.SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
423	261.	188.	183.	158.	540.	0.88	0.54	1.10	15.3	0.54
424	300.	179.	174.	150.	510.	0.80	0.35	1.09	14.7	0.48
425	302.	178.	175.	146.	540.	0.82	0.35	1.09	14.7	0.50
426	303.	175.	173.	158.	540.	0.80	0.77	1.10	15.3	0.77
427	306.	185.	180.	155.	520.	0.75	0.20	1.13	21.6	0.39
428	344.	183.	177.	158.	550.	0.72	0.37	1.09	14.7	0.50
429	341.	183.	180.	163.	550.	0.75	0.35	1.09	14.7	0.48
430	341.	185.	180.	160.	540.	0.68	0.38	1.13	21.6	0.72
432	270.	151.	150.	140.	540.	0.94	0.21	1.10	21.7	0.0
433	270.	155.	152.	134.	525.	0.92	0.23	1.10	21.7	0.31
434	273.	157.	153.	134.	535.	0.93	0.23	1.10	21.7	0.63
441A	347.	186.	182.	154.	510.	0.70	0.23	1.13	21.6	0.63
441B	331.	168.	164.	145.	500.	0.66	0.23	1.13	21.6	0.42
441C	328.	178.	174.	147.	500.	0.70	0.23	1.13	21.6	0.25
441D	340.	176.	173.	149.	515.	0.66	0.23	1.13	21.6	0.0
501	342.	184.	183.	153.	505.	0.65	0.28	1.12	19.2	0.0
501R	341.	180.	176.	154.	525.	0.73	0.41	1.06	11.3	0.0
502	341.	182.	179.	153.	540.	1.20	0.33	1.12	19.2	0.0
503	342.	182.	180.	158.	540.	0.98	0.30	1.12	19.2	0.0
503R	350.	188.	183.	152.	535.	1.00	0.51	1.06	11.3	0.0
504	342.	182.	179.	160.	515.	0.49	0.25	1.09	13.8	0.0
504R	336.	175.	170.	142.	485.	0.50	0.32	1.06	11.3	0.0
505	313.	164.	162.	137.	480.	0.32	0.21	1.09	13.8	0.0
505R	323.	160.	157.	143.	490.	0.30	0.26	1.06	11.3	0.0
506	258.	178.	172.	162.	530.	0.87	0.91	1.05	11.4	0.0

TABLE A.5. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
RUN	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
423	6307..	4547.	4276.	4243.	4558.	9.6	2.3	45.6	196.4
424	5923.	4640.	4138.	4106.	4460.	10.0	2.2	28.1	92.0
425	6088.	4639.	4233.	4213.	4523.	9.7	2.2	28.1	95.9
426	6014.	4588.	4046.	4033.	4169.	10.2	2.1	65.0	280.1
427	5764.	4505.	4023.	3992.	4208.	10.2	2.1	24.3	74.8
428	5733.	4564.	3861.	3825.	4024.	10.7	2.0	29.8	103.9
429	5852.	4641.	3974.	3955.	4077.	10.4	2.1	28.1	99.7
430	5544.	4441.	4040.	4009.	4113.	10.2	2.1	46.2	136.9
432	6518.	4759.	4208.	4201.	4486.	9.8	2.2	25.1	0.0
433	6400.	4743.	4221.	4201.	4437.	9.8	2.2	27.5	39.9
434	6468.	4765.	4349.	4321.	4556.	9.5	2.3	27.5	81.0
441A	5540.	4609.	4167.	4141.	4344.	9.9	2.2	28.0	119.8
441B	5352.	4410.	3956.	3931.	4180.	10.4	2.1	28.0	79.9
441C	5511.	4524.	4127.	4101.	4306.	10.0	2.2	28.0	47.5
441D	5393.	4425.	3976.	3957.	4176.	10.4	2.1	28.0	0.0
501	5325.	4425.	4056.	4050.	4077.	10.2	2.1	30.2	0.0
501R	5701.	4636.	3965.	3940.	4294.	10.4	2.1	24.6	0.0
502	7365.	5899.	5063.	5040.	5479.	8.1	2.7	35.6	0.0
503	6656.	5338.	4572.	4558.	4827.	9.0	2.4	32.4	0.0
503R	6706.	5460.	4676.	4640.	4843.	9.8	2.5	30.6	0.0
504	4647.	3823.	3367.	3352.	3672.	12.2	1.8	18.8	0.0
504R	4622.	3893.	3418.	3391.	3659.	12.1	1.8	19.2	0.0
505	3687.	3032.	2771.	2763.	2889.	14.9	1.5	15.8	0.0
505R	3589.	2958.	2584.	2572.	2848.	16.0	1.4	15.6	0.0
506	6243.	4525.	4354.	4312.	4309.	9.5	2.3	54.8	0.0

TABLE A.5. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIC	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
423	4.3	22.5	13.3	10.1	40.6	24.7	55.2	1.75	32.
424	3.3	22.0	12.0	10.3	45.7	14.0	53.3	1.10	48.
425	3.4	21.7	11.2	8.2	48.2	26.9	62.2	1.12	55.
426	4.3	21.4	7.6	3.6	64.7	52.9	83.4	2.62	32.
427	3.1	20.9	13.7	11.1	34.5	18.8	46.9	1.00	47.
428	3.5	19.7	8.2	6.0	58.5	26.5	69.5	1.30	53.
429	3.5	19.4	8.7	5.2	55.1	40.4	73.2	1.26	58.
430	3.0	19.0	7.4	4.4	60.9	41.2	77.0	2.10	37.
432	0.0	23.2	14.5	11.2	37.4	23.1	51.9	0.93	56.
433	1.5	24.3	10.3	7.9	57.7	23.2	67.5	0.98	69.
434	2.9	22.0	8.4	6.4	62.0	23.4	70.9	1.08	66.
441A	4.3	20.3	11.1	8.7	45.6	21.3	57.2	1.19	48.
441B	2.9	19.6	9.1	5.5	53.4	40.2	72.1	1.23	59.
441C	1.7	19.7	10.8	6.2	45.1	42.3	68.3	1.23	56.
441D	0.0	18.5	10.4	9.6	43.5	7.6	47.8	1.31	37.
501	0.0	18.9	9.4	7.6	50.2	19.3	59.8	1.38	43.
501R	0.0	20.5	10.9	9.2	46.8	15.3	55.0	1.04	53.
502	0.0	25.9	14.2	13.0	45.1	8.8	49.9	1.19	42.
503	0.0	22.4	12.5	10.8	44.1	13.6	51.7	1.25	41.
503R	0.0	23.1	13.3	10.8	42.4	19.0	53.3	1.14	47.
504	0.0	17.0	9.2	8.1	45.7	12.5	52.4	0.96	55.
504R	0.0	16.7	9.3	7.2	43.9	22.8	56.7	1.00	57.
505	0.0	12.8	6.2	3.6	51.0	42.1	71.7	1.07	67.
505R	0.0	12.4	5.2	3.4	57.8	34.4	72.3	1.09	66.
506	0.0	23.6	15.3	11.6	35.1	24.4	50.9	2.01	25.

TABLE A.6. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
507	0.0	0.0	800.	370.	300.	6.5	8.1	8.9	129.	127.
508	0.0	0.0	800.	375.	310.	5.5	6.0	7.5	129.	127.
508R	0.0	0.0	820.	430.	340.	4.5	6.0	7.5	130.	127.
509	0.0	0.0	835.	425.	335.	4.5	6.0	7.5	130.	128.
510	0.0	0.0	860.	500.	370.	4.0	4.5	5.5	128.	126.
511	0.0	0.0	735.	370.	310.	5.0	5.7	7.0	129.	127.
512	0.0	0.0	765.	330.	265.	5.5	6.0	8.5	130.	127.
512R	0.0	0.0	820.	330.	220.	5.5	6.0	8.5	130.	132.
513	0.0	0.0	700.	350.	280.	3.5	4.0	5.5	129.	126.
514	0.0	0.0	780.	280.	120.	3.5	4.0	5.5	127.	124.
515	0.0	0.0	780.	530.	350.	3.0	4.0	6.0	130.	132.
516	0.0	0.0	790.	525.	410.	5.4	6.2	7.1	130.	128.
516A	0.0	0.0	785.	500.	360.	3.0	4.0	6.0	130.	128.
517	0.0	0.0	830.	545.	445.	4.0	4.5	6.0	130.	134.
518	0.0	0.0	810.	550.	415.	6.0	6.3	7.2	123.	120.
519	0.0	0.0	800.	410.	310.	2.0	2.5	4.5	130.	128.
520	0.0	0.0	790.	395.	275.	3.5	4.0	5.0	127.	124.
521	0.0	0.0	780.	360.	265.	5.0	6.1	6.6	128.	126.
522	0.0	0.0	825.	385.	265.	5.2	5.7	6.3	130.	128.
523	0.0	0.0	780.	355.	260.	4.5	5.0	6.0	128.	126.
524	0.0	0.0	795.	385.	325.	4.5	5.0	6.5	130.	128.
524A	0.0	0.0	770.	350.	230.	4.5	5.0	6.5	129.	126.
525	0.0	0.0	820.	390.	310.	3.5	4.0	5.0	128.	127.
526	0.0	0.0	840.	350.	230.	3.0	4.0	6.0	130.	128.
526A	0.0	0.0	810.	300.	210.	3.0	4.0	6.0	130.	129.

TABLE A.6. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
RUN	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
507	342.	180.	176.	159.	510.	1.18	0.37	1.09	14.7	0.0
508	342.	182.	177.	160.	530.	0.73	0.29	1.09	14.7	0.0
508R	342.	182.	179.	150.	525.	0.72	0.47	1.06	10.0	0.0
509	342.	182.	178.	161.	520.	0.48	0.25	1.09	14.7	0.0
510	328.	168.	165.	154.	480.	0.31	0.22	1.09	14.7	0.0
511	346.	186.	182.	161.	550.	1.18	0.51	1.06	11.2	0.0
512	343.	184.	132.	163.	540.	0.72	0.41	1.06	11.2	0.0
512R	338.	177.	174.	157.	510.	0.70	0.39	1.06	12.2	0.0
513	341.	181.	177.	161.	510.	0.50	0.33	1.06	11.2	0.0
514	311.	153.	150.	136.	490.	0.30	0.25	1.07	12.0	0.0
515	258.	179.	177.	158.	530.	1.13	0.32	1.11	17.1	0.0
516	265.	185.	182.	162.	545.	0.95	0.29	1.11	17.1	0.0
516R	267.	183.	178.	150.	500.	0.59	0.40	1.06	11.3	0.0
517	260.	102.	177.	150.	490.	1.15	0.32	1.10	17.1	0.0
518	266.	187.	183.	141.	460.	0.60	0.27	1.09	14.7	0.0
519	260.	172.	168.	147.	530.	1.20	0.58	1.06	11.2	0.0
520	252.	165.	162.	140.	510.	0.60	0.41	1.06	11.2	0.0
521	344.	185.	182.	152.	500.	1.06	0.62	1.11	17.1	0.0
522	343.	183.	180.	156.	530.	0.75	0.48	1.11	17.1	0.0
523	337.	179.	175.	153.	510.	1.18	0.40	1.09	14.7	0.0
524	340.	178.	174.	154.	510.	0.73	0.29	1.09	14.7	0.0
524R	345.	182.	177.	145.	530.	0.73	0.91	1.06	10.0	0.0
525	341.	102.	180.	152.	535.	1.19	0.73	1.08	15.1	0.0
526	340.	180.	173.	151.	520.	0.73	0.58	1.08	15.1	0.0
526R	342.	182.	177.	156.	505.	0.73	0.76	1.06	12.2	0.0

TABLE A.6. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE							SLURRY FEED RATE	
RUN (NO.)	ENTER COOLER (ACFM)	ENTER S.D. (ACFM)	EXIT S.D. (ACFM)	ENTER F.F. (ACFM)	EXIT F.F. (ACFM)	SPRAY DRYER RESIDENCE TIME (SEC)	FABRIC FILTER AIR-TO-CLOTH RATIO (FT/MIN)	LIME (LB/HR)	RECYCLE (LB/HR)
507	7193.	5947.	5470.	5436.	5619.	7.5	2.9	29.7	0.0
508	5716.	4630.	3970.	3939.	4217.	10.4	2.1	23.2	0.0
508R	5662.	4610.	4177.	4158.	4366.	9.9	2.2	24.9	0.0
509	4611.	3774.	3419.	3398.	3638.	12.1	1.8	20.0	0.0
510	3629.	3042.	2590.	2578.	2686.	15.9	1.4	17.6	0.0
511	7340.	5857.	5084.	5053.	5303.	8.1	2.7	30.2	0.0
512	5705.	4581.	3934.	3922.	4440.	10.5	2.1	24.3	0.0
512R	5540.	4558.	3898.	3879.	4404.	10.6	2.1	25.1	0.0
513	4682.	3866.	3302.	3282.	3481.	12.5	1.7	19.5	0.0
514	3589.	2913.	2471.	2459.	2614.	16.7	1.3	16.0	0.0
515	7111.	5157.	4935.	4919.	5334.	8.4	2.6	30.3	0.0
516	6569.	4739.	4516.	4495.	4620.	9.1	2.4	27.4	0.0
516R	5060.	3832.	3648.	3620.	3868.	11.3	1.9	24.0	0.0
517	7027.	5326.	4978.	4940.	5160.	8.3	2.6	30.1	0.0
518	4995.	3942.	3650.	3627.	3598.	11.3	1.9	21.6	0.0
519	7328.	5330.	4901.	4870.	5216.	8.4	2.6	34.4	0.0
520	5129.	3765.	3469.	3452.	3526.	11.9	1.8	24.3	0.0
521	6782.	5680.	5052.	5029.	4954.	8.2	2.7	58.6	0.0
522	5793.	4699.	4028.	4009.	4010.	10.2	2.1	45.4	0.0
523	7193.	5910.	5063.	5032.	5161.	8.1	2.7	32.1	0.0
524	5658.	4666.	3980.	3955.	4189.	10.4	2.1	23.2	0.0
524R	5716.	4648.	3965.	3934.	4087.	10.4	2.1	48.1	0.0
525	7316.	5889.	5037.	5021.	5084.	8.2	2.7	59.6	0.0
526	5687.	4642.	4067.	4023.	4340.	10.1	2.1	47.3	0.0
526R	5643.	4690.	4112.	4080.	4409.	10.0	2.2	49.0	0.0

TABLE A.6. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } CA(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } CA(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
507	0.0	26.1	13.9	12.0	46.7	13.9	54.1	0.98	55.
508	0.0	20.3	10.2	9.3	49.8	9.1	54.3	0.99	55.
508R	0.0	20.7	12.3	10.7	40.6	13.0	48.4	1.04	47.
509	0.0	17.3	10.0	8.6	42.4	13.3	50.0	1.00	50.
510	0.0	14.6	9.1	7.1	37.9	21.5	51.3	1.04	49.
511	0.0	23.5	12.8	11.6	45.5	9.1	50.4	1.11	45.
512	0.0	19.2	8.9	8.3	53.8	6.3	56.7	1.09	52.
512R	0.0	20.6	8.9	6.9	56.9	22.2	66.5	1.05	63.
513	0.0	14.9	7.9	6.9	46.6	12.9	53.5	1.14	47.
514	0.0	13.0	5.0	2.3	61.7	53.4	82.1	1.07	77.
515	0.0	24.6	18.0	13.3	26.9	26.2	46.1	1.06	43.
516	0.0	22.7	16.2	13.4	28.8	17.2	41.0	1.04	39.
516R	0.0	18.2	12.5	10.0	31.4	19.5	44.8	1.14	39.
517	0.0	27.0	18.6	16.6	31.2	10.9	38.7	0.96	40.
518	0.0	19.3	13.6	10.9	29.5	19.9	43.5	0.97	45.
519	0.0	26.0	14.0	11.7	46.3	16.2	55.0	1.14	48.
520	0.0	18.4	9.6	7.1	47.5	26.3	61.3	1.14	54.
521	0.0	24.2	12.4	9.4	48.8	23.9	61.1	2.09	29.
522	0.0	21.2	10.6	7.6	50.0	28.5	64.3	1.85	35.
523	0.0	25.4	12.4	9.6	51.4	22.2	62.2	1.09	57.
524	0.0	20.4	10.6	9.8	48.2	7.7	52.2	0.98	53.
524R	0.0	19.5	9.5	6.8	51.4	28.1	65.1	2.13	31.
525	0.0	20.5	13.5	11.3	49.3	15.8	57.3	1.94	30.
526	0.0	21.4	9.8	7.2	54.4	26.6	66.5	1.91	35.
526R	0.0	20.3	8.4	6.4	59.4	21.8	68.3	2.03	34.

TABLE A.7. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
529	0.0	0.0	825.	545.	430.	3.0	4.0	6.0	130.	127.
530	0.0	0.0	790.	450.	360.	3.0	4.0	6.0	130.	128.
531	0.0	0.0	815.	465.	330.	3.0	4.0	6.0	130.	128.
532	0.0	0.0	810.	450.	320.	3.0	4.0	6.0	130.	130.
533	0.0	0.0	780.	400.	310.	3.0	4.0	6.0	130.	130.
534	0.0	0.0	780.	390.	295.	3.0	4.0	6.0	130.	126.
535	0.0	0.0	790.	380.	300.	3.0	4.0	6.0	128.	124.
536	0.0	0.0	775.	350.	250.	3.0	4.0	6.0	130.	130.
537	0.0	0.0	780.	410.	300.	3.0	4.0	6.0	130.	128.
538	0.0	0.0	780.	405.	320.	3.0	4.0	6.0	130.	127.
539	1.2	33.5	775.	425.	290.	3.0	4.0	6.0	130.	126.
540	1.2	33.5	795.	400.	300.	3.0	4.0	6.0	130.	126.
541	1.2	33.5	800.	500.	420.	3.0	4.0	6.0	130.	126.
542	1.2	33.5	820.	370.	280.	3.0	4.0	6.0	130.	126.
543	1.2	33.5	805.	462.	345.	3.0	4.0	6.0	130.	127.
601	0.0	0.0	800.	510.	420.	3.0	3.5	5.0	124.	120.
602R	1.0	9.6	810.	490.	390.	5.5	6.0	7.0	122.	119.
603	1.0	8.0	790.	380.	310.	4.9	5.0	7.3	127.	122.
604	1.2	35.0	800.	490.	325.	5.0	6.0	7.5	127.	123.
605	1.2	35.0	700.	350.	280.	3.0	3.5	5.0	125.	121.
606	1.0	9.6	850.	510.	410.	5.5	5.7	6.9	126.	122.
607	0.0	0.0	790.	465.	380.	5.0	6.0	7.9	120.	121.
608R	1.1	10.0	810.	430.	370.	4.7	5.0	7.0	126.	121.
609	1.1	16.9	730.	415.	335.	5.5	6.0	7.0	124.	120.
610	1.1	21.2	700.	435.	340.	5.0	5.5	6.5	126.	123.

TABLE A.7. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.C.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
529	344.	185.	182.	151.	535.	1.19	0.47	1.07	12.0	0.0
530	343.	185.	184.	158.	530.	0.73	0.38	1.07	12.0	0.0
531	340.	181.	180.	159.	510.	0.48	0.30	1.07	12.0	0.0
532	331.	170.	168.	151.	500.	0.28	0.25	1.07	12.0	0.0
533	337.	177.	173.	157.	535.	0.71	0.38	1.07	12.0	0.0
534	338.	177.	175.	147.	525.	1.02	0.48	1.07	12.0	0.0
535	343.	183.	180.	156.	535.	0.73	0.37	1.07	12.0	0.0
536	339.	179.	175.	159.	520.	0.51	0.31	1.07	12.0	0.0
537	344.	184.	182.	157.	500.	0.33	0.24	1.06	11.3	0.0
538	341.	182.	180.	159.	510.	0.72	0.40	1.06	11.3	0.0
539	340.	178.	175.	143.	545.	1.10	0.46	1.11	12.5	0.45
540	340.	180.	175.	147.	520.	0.73	0.35	1.11	12.5	0.35
541	335.	174.	170.	145.	490.	0.48	0.29	1.11	12.5	0.29
542	318.	160.	159.	140.	485.	0.31	0.25	1.11	12.5	0.22
543	343.	183.	180.	149.	510.	0.72	0.35	1.11	12.5	0.35
601	301.	183.	180.	156.	530.	0.77	0.28	1.09	15.5	0.0
602R	310.	190.	186.	145.	510.	0.75	0.28	1.08	17.1	0.31
603	303.	173.	167.	141.	530.	0.81	0.28	1.08	17.1	0.28
604	300.	180.	176.	146.	520.	0.80	0.27	1.11	16.4	0.25
605	304.	181.	177.	147.	550.	0.78	0.27	1.11	16.4	0.35
606	301.	182.	179.	161.	530.	0.77	0.28	1.08	17.1	0.31
607	305.	179.	174.	147.	520.	0.79	0.28	1.11	16.4	0.0
608R	299.	178.	174.	146.	525.	0.82	0.29	1.10	15.8	0.25
609	301.	179.	176.	152.	540.	0.80	0.29	1.10	15.8	0.25
610	304.	180.	176.	148.	540.	0.80	0.29	1.10	15.8	0.42

TABLE A.7. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
529	7316.	5912.	5193.	5169.	5498.	7.9	2.7	30.1	0.0
530	5716.	4636.	4077.	4070.	4366.	10.1	2.2	24.4	0.0
531	4588.	3784.	3320.	3314.	3583.	12.4	1.8	19.2	0.0
532	3486.	2872.	2506.	2498.	2716.	16.4	1.3	16.0	0.0
533	5651.	4526.	3962.	3937.	4289.	10.4	2.1	24.4	0.0
534	6739.	5460.	4774.	4759.	5085.	8.6	2.5	30.8	0.0
535	5730.	4624.	4056.	4037.	4342.	10.2	2.1	23.7	0.0
536	4753.	3875.	3394.	3373.	3675.	12.1	1.8	19.9	0.0
537	3784.	3169.	2780.	2772.	2977.	14.8	1.5	14.4	0.0
538	5619.	4640.	4072.	4059.	4388.	10.1	2.2	24.0	0.0
539	7069.	5627.	4917.	4894.	5194.	8.4	2.6	32.0	92.4
540	5687.	4642.	4067.	4036.	4312.	10.1	2.1	24.3	71.9
541	4540.	3799.	3319.	3298.	3540.	12.4	1.7	20.1	59.6
542	3639.	2996.	2614.	2609.	2827.	15.8	1.4	17.4	45.2
543	5619.	4651.	4079.	4060.	4318.	10.1	2.2	24.3	71.9
601	5870.	4512.	4027.	4008.	4189.	10.2	2.1	23.7	0.0
602R	5735.	4552.	4079.	4053.	4049.	10.1	2.2	25.9	15.2
603	6021.	4640.	3992.	3954.	4335.	10.3	2.1	25.9	11.7
604	5953.	4617.	4247.	4221.	4424.	9.7	2.2	24.6	53.4
605	5967.	4514.	4005.	3980.	4118.	10.3	2.1	24.6	74.7
606	5870.	4512.	3964.	3945.	4135.	10.4	2.1	25.9	15.2
607	5916.	4618.	4220.	4187.	4516.	9.8	2.2	25.5	0.0
608R	6042.	4656.	4099.	4073.	4380.	10.1	2.2	25.2	13.4
609	6014.	4576.	4080.	4061.	4168.	10.1	2.2	25.2	23.0
610	6014.	4594.	4085.	4059.	4131.	10.1	2.2	25.2	50.8

TABLE A.7. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
529	0.0	26.7	19.3	17.0	27.7	11.8	36.2	0.98	37.
530	0.0	20.1	12.5	11.2	37.6	10.6	44.2	1.05	42.
531	0.0	16.9	10.6	8.4	37.5	20.7	50.4	0.98	51.
532	0.0	12.9	7.9	6.3	39.1	20.5	51.6	1.07	48.
533	0.0	19.5	10.9	9.5	43.8	13.4	51.4	1.08	48.
534	0.0	23.5	12.9	10.9	45.2	15.5	53.7	1.13	47.
535	0.0	20.0	10.5	9.3	47.3	11.8	53.5	1.02	52.
536	0.0	16.5	8.2	6.5	50.5	20.2	60.5	1.04	58.
537	0.0	13.5	7.8	6.4	42.4	18.2	52.9	0.92	58.
538	0.0	19.9	11.3	10.0	43.1	11.7	49.8	1.04	48.
539	2.9	24.0	14.4	11.0	39.9	23.7	54.2	1.15	47.
540	3.0	20.3	11.2	9.4	44.9	16.2	53.8	1.04	52.
541	3.0	16.8	11.5	10.8	31.5	6.1	35.7	1.04	35.
542	2.6	13.9	6.9	5.8	50.6	15.4	58.2	1.08	54.
543	3.0	20.5	12.9	10.8	37.1	16.5	47.5	1.02	46.
601	0.0	20.9	14.0	12.6	32.7	10.6	39.8	0.98	41.
602R	0.6	21.1	13.5	11.5	35.8	15.1	45.5	1.06	43.
603	0.5	21.1	10.5	9.8	50.1	6.7	53.5	1.06	51.
604	2.2	21.4	14.3	10.4	33.1	27.0	51.2	1.00	51.
605	3.0	18.2	9.6	8.4	47.1	13.1	54.1	1.17	46.
606	0.6	22.2	13.8	12.0	37.5	13.3	45.8	1.01	45.
607	0.0	21.0	13.5	12.4	35.6	7.9	40.7	1.05	39.
608R	0.5	21.8	12.1	11.8	44.4	3.2	46.2	1.00	46.
609	0.9	19.3	11.7	10.0	39.6	13.9	48.0	1.13	43.
610	2.0	20.1	12.2	10.2	39.3	16.8	49.5	1.08	46.

TABLE A.8. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
611	1.2	31.7	750.	500.	365.	4.2	5.4	6.8	125.	121.
612	1.1	10.0	750.	480.	350.	4.8	5.5	7.5	125.	120.
613	0.0	0.0	790.	500.	400.	3.0	3.5	5.0	125.	121.
614	1.1	11.1	755.	495.	370.	5.5	6.0	7.6	125.	121.
615	1.1	17.3	765.	500.	385.	5.2	5.7	7.6	128.	123.
616	1.1	21.6	765.	430.	330.	4.5	5.5	7.0	125.	120.
617	1.1	21.6	770.	435.	320.	4.5	5.6	6.7	123.	119.
618	1.1	11.1	790.	380.	310.	5.0	5.7	7.5	126.	121.
619	0.0	0.0	810.	490.	400.	4.5	5.5	6.5	126.	120.
620	1.1	7.8	785.	465.	390.	5.2	5.9	6.5	123.	120.
621	1.1	14.5	850.	380.	330.	5.1	5.7	7.6	127.	122.
622	1.1	14.5	760.	420.	340.	4.0	4.9	6.6	125.	120.
623	1.2	23.1	750.	430.	320.	5.0	5.6	7.5	123.	118.
624	1.1	7.8	780.	460.	380.	5.2	5.8	8.2	129.	123.
801	0.0	0.0	750.	540.	480.	7.2	7.3	8.8	125.	120.
802	0.0	0.0	770.	490.	420.	7.1	7.4	8.7	125.	120.
803	0.0	0.0	780.	480.	400.	6.9	7.0	8.9	123.	118.
804	0.0	0.0	810.	450.	370.	7.0	7.0	8.6	123.	118.
805	0.0	0.0	750.	500.	420.	7.3	7.4	8.8	125.	121.
806	0.0	0.0	850.	775.	635.	4.5	5.0	7.0	125.	120.
807	0.0	0.0	800.	570.	440.	4.5	5.1	7.0	127.	122.
808	0.0	0.0	760.	510.	375.	4.5	5.0	7.5	126.	120.
809	0.0	0.0	780.	600.	390.	4.5	4.8	6.9	125.	120.
810	0.0	0.0	770.	550.	440.	4.5	5.0	7.0	122.	117.
811	0.0	0.0	710.	620.	540.	5.0	6.0	7.5	124.	119.

TABLE A.8. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
611	305.	185.	193.	155.	530.	0.82	0.29	1.10	15.8	0.40
612	298.	180.	175.	148.	540.	0.82	0.29	1.10	15.8	0.47
613	297.	175.	178.	148.	525.	0.77	0.28	1.12	16.4	0.0
614	304.	180.	177.	160.	530.	0.77	0.29	1.10	15.8	0.25
615	298.	180.	175.	162.	550.	0.80	0.29	1.10	15.8	0.25
616	301.	181.	179.	160.	550.	0.79	0.29	1.10	15.8	0.40
617	302.	184.	180.	155.	540.	0.79	0.29	1.10	15.8	0.61
618	304.	181.	178.	154.	540.	0.80	0.29	1.10	15.8	0.42
619	299.	181.	175.	151.	515.	0.80	0.28	1.08	17.1	0.0
620	298.	181.	177.	151.	530.	0.79	0.29	1.10	15.8	0.33
621	306.	184.	181.	167.	545.	0.74	0.29	1.10	15.8	0.66
622	302.	182.	177.	160.	540.	0.76	0.29	1.10	15.8	0.40
623	297.	176.	172.	147.	530.	0.77	0.29	1.10	15.8	0.55
624	295.	177.	173.	160.	500.	0.79	0.29	1.10	15.8	0.66
801	304.	182.	178.	156.	520.	0.81	0.26	1.07	10.3	0.0
802	305.	182.	180.	155.	530.	0.82	0.45	1.07	10.3	0.0
803	305.	184.	182.	148.	530.	0.83	0.68	1.07	10.3	0.0
804	304.	182.	179.	149.	520.	0.84	0.91	1.07	10.3	0.0
805	305.	183.	179.	155.	520.	0.83	0.46	1.07	10.3	0.0
806	305.	186.	180.	160.	540.	0.81	0.36	1.03	6.8	0.0
807	303.	181.	179.	156.	545.	0.84	0.38	1.10	12.0	0.0
808	307.	185.	181.	152.	505.	0.82	0.57	1.10	12.0	0.0
809	305.	191.	186.	147.	495.	0.81	0.76	1.10	12.0	0.0
810	303.	185.	181.	155.	540.	0.82	0.71	1.03	6.8	0.0
811	301.	181.	178.	149.	535.	0.82	0.28	1.05	8.8	0.0

TABLE A.8. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
611	6058.	4681.	4348.	4334.	4518.	9.5	2.3	25.2	76.7
612	6088.	4615.	4178.	4145.	4481.	9.9	2.2	25.2	25.5
613	5855.	4500.	3991.	4010.	4149.	10.3	2.1	25.7	0.0
614	5870.	4530.	4031.	4012.	4322.	10.2	2.1	25.2	15.0
615	6044.	4536.	4060.	4029.	4436.	10.2	2.1	25.2	24.0
616	6006.	4525.	4156.	4144.	4409.	9.9	2.2	25.2	49.2
617	5976.	4554.	4219.	4193.	4317.	9.8	2.2	25.2	75.1
618	6014.	4594.	4140.	4120.	4432.	10.0	2.2	25.2	25.2
619	5939.	4622.	4255.	4215.	4318.	9.7	2.2	25.9	0.0
620	5946.	4552.	4131.	4105.	4094.	10.0	2.2	25.2	13.4
621	5798.	4419.	3966.	3948.	4341.	10.4	2.1	25.2	50.7
622	5861.	4466.	4074.	4042.	4350.	10.1	2.1	25.2	30.7
623	5870.	4489.	4024.	3998.	4314.	10.2	2.1	25.2	74.3
624	5855.	4605.	4144.	4118.	4671.	9.9	2.2	25.2	26.9
801	5990.	4670.	4066.	4041.	4328.	10.1	2.1	14.4	0.0
802	6059.	4681.	4129.	4116.	4334.	10.0	2.2	25.0	0.0
803	6095.	4709.	4106.	4093.	4403.	10.0	2.2	37.7	0.0
804	6100.	4756.	4111.	4092.	4345.	10.0	2.2	50.5	0.0
805	6064.	4733.	4122.	4097.	4349.	10.0	2.2	25.5	0.0
806	6051.	4629.	4140.	4102.	4470.	10.0	2.2	12.5	0.0
807	6177.	4690.	4200.	4187.	4519.	9.8	2.2	25.1	0.0
808	5981.	4754.	4237.	4210.	4648.	9.7	2.2	37.7	0.0
809	5913.	4737.	4214.	4182.	4439.	9.8	2.2	50.3	0.0
810	6088.	4645.	4158.	4132.	4460.	9.9	2.2	24.7	0.0
811	6073.	4645.	4274.	4254.	4467.	9.6	2.3	13.0	0.0

TABLE A.8. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
611	3.0	20.2	14.8	11.8	26.6	20.4	41.6	1.08	39.
612	1.0	20.1	13.8	11.3	31.4	17.7	43.5	1.08	40.
613	0.0	20.6	13.8	12.0	33.1	13.1	41.9	1.07	39.
614	0.6	19.7	13.7	11.3	30.4	17.3	42.4	1.11	38.
615	1.0	20.1	13.9	12.1	30.7	13.4	40.0	1.08	37.
616	2.0	20.0	12.3	10.3	38.7	15.8	48.4	1.09	44.
617	3.0	20.2	12.5	9.9	38.1	21.2	51.2	1.08	48.
618	1.0	20.9	10.8	9.8	48.3	8.8	52.9	1.04	51.
619	0.0	21.7	14.3	12.4	34.1	13.1	42.7	1.03	41.
620	0.5	20.7	13.2	11.5	36.4	12.8	44.6	1.05	42.
621	2.0	21.6	10.3	10.0	52.3	2.4	53.4	1.01	53.
622	1.2	19.6	11.7	10.5	40.2	10.5	46.5	1.11	42.
623	2.9	19.6	12.0	10.0	38.8	16.4	48.9	1.11	44.
624	1.1	20.9	13.2	12.6	37.1	4.3	39.8	1.04	38.
801	0.0	20.2	15.0	14.8	25.4	1.4	26.4	0.62	43.
802	0.0	20.7	13.9	13.0	33.1	6.1	37.2	1.04	36.
803	0.0	21.1	13.5	12.7	36.3	5.4	39.7	1.54	26.
804	0.0	22.2	12.7	11.6	42.9	8.4	47.6	1.97	24.
805	0.0	20.4	14.1	13.1	30.9	7.4	36.0	1.08	33.
906	0.0	22.6	21.8	20.1	3.4	7.8	11.0	0.48	23.
807	0.0	21.6	16.4	14.2	24.0	13.6	34.4	1.00	34.
808	0.0	20.7	14.7	12.5	28.9	15.0	39.5	1.57	25.
809	0.0	21.2	17.1	12.5	19.6	26.6	41.0	2.05	20.
810	0.0	20.6	15.6	14.0	24.4	10.0	31.9	1.04	31.
811	0.0	19.1	18.2	17.4	4.6	4.2	8.6	0.59	15.

TABLE A.9. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
812	0.0	0.0	770.	480.	390.	4.2	5.0	7.5	125.	119.
813	0.0	0.0	810.	430.	340.	5.0	6.0	7.5	125.	120.
814	0.0	0.0	775.	450.	300.	5.0	6.2	7.5	123.	119.
815	0.0	0.0	860.	590.	490.	5.0	6.0	7.5	122.	118.
816	0.0	0.0	810.	650.	560.	5.0	5.5	7.0	124.	119.
817	0.0	0.0	820.	530.	420.	4.6	4.9	6.8	127.	122.
818	0.0	0.0	780.	440.	360.	5.0	5.5	7.0	122.	118.
819	0.0	0.0	740.	400.	310.	5.0	5.5	7.0	124.	119.
820	0.0	0.0	780.	480.	420.	5.0	5.5	7.0	124.	119.
821	0.0	0.0	810.	600.	540.	5.2	6.3	7.3	125.	122.
822	0.0	0.0	810.	550.	480.	5.5	6.0	7.5	125.	120.
823	0.0	0.0	810.	500.	400.	5.0	5.5	7.0	125.	120.
824	0.0	0.0	790.	400.	330.	5.0	5.5	7.0	122.	118.
825	0.0	0.0	760.	460.	400.	4.9	5.5	7.2	127.	122.
826	0.0	0.0	760.	650.	480.	5.0	6.0	7.5	122.	118.
827	0.0	0.0	790.	500.	410.	5.0	6.0	7.5	122.	118.
828	0.0	0.0	790.	440.	310.	5.0	5.5	7.5	124.	119.
829	0.0	0.0	800.	410.	290.	5.1	5.9	7.4	125.	120.
830	0.0	0.0	820.	590.	480.	5.0	5.7	7.3	125.	120.
831	0.0	0.0	840.	635.	600.	6.0	6.3	8.1	126.	123.
832	0.0	0.0	825.	500.	450.	5.9	5.9	7.8	127.	122.
833	0.0	0.0	800.	460.	370.	6.0	6.5	8.0	124.	119.
834	0.0	0.0	810.	440.	360.	6.0	6.5	7.5	121.	118.
835	0.0	0.0	850.	510.	450.	5.8	6.5	7.8	120.	122.
836	0.0	0.0	800.	610.	550.	5.0	5.5	6.5	125.	121.

TABLE A.9. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL $\triangle P$	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
812	301.	181.	179.	156.	530.	0.84	0.42	1.07	10.7	0.0
813	306.	182.	178.	153.	525.	0.82	0.74	1.07	10.7	0.0
814	303.	182.	170.	145.	510.	0.84	0.83	1.07	10.7	0.0
815	303.	183.	179.	150.	535.	0.82	0.54	1.07	8.8	0.0
816	304.	182.	179.	150.	540.	0.86	0.28	1.08	10.0	0.0
817	308.	186.	183.	156.	530.	0.83	0.26	1.11	17.1	0.0
818	308.	186.	181.	153.	530.	0.82	0.39	1.11	17.1	0.0
819	302.	182.	178.	151.	530.	0.82	0.53	1.11	17.1	0.0
820	301.	183.	178.	144.	520.	0.87	0.48	1.11	10.0	0.0
821	301.	182.	179.	159.	545.	0.81	0.29	1.06	8.2	0.0
822	304.	188.	184.	159.	550.	0.81	0.42	1.06	11.3	0.0
823	306.	185.	182.	152.	540.	0.81	0.63	1.06	11.3	0.0
824	297.	173.	170.	138.	530.	0.83	0.84	1.06	11.3	0.0
825	300.	177.	176.	156.	550.	0.84	0.58	1.06	8.2	0.0
826	301.	181.	179.	148.	500.	0.82	0.25	1.06	10.8	0.0
827	303.	182.	178.	153.	530.	0.82	0.33	1.09	14.6	0.0
828	298.	179.	176.	156.	540.	0.84	0.50	1.09	14.6	0.0
829	302.	181.	178.	151.	540.	0.83	0.66	1.09	14.6	0.0
830	306.	187.	183.	157.	530.	0.84	0.44	1.06	10.8	0.0
831	306.	185.	180.	158.	510.	0.81	0.26	1.06	9.1	0.0
832	305.	186.	183.	156.	510.	0.82	0.40	1.07	11.6	0.0
833	302.	181.	176.	149.	510.	0.82	0.60	1.07	11.6	0.0
834	300.	180.	176.	143.	510.	0.82	0.81	1.07	11.6	0.0
835	307.	185.	182.	152.	510.	0.83	0.53	1.06	9.1	0.0
836	311.	190.	185.	161.	540.	0.31	0.28	1.07	8.4	0.0

TABLE A.9. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE							SLURRY FEED RATE	
RUN (NO.)	ENTER COOLER (ACFM)	ENTER S.D. (ACFM)	EXIT S.D. (ACFM)	ENTER F.F. (ACFM)	EXIT F.F. (ACFM)	SPRAY DRYER RESIDENCE TIME (SEC)	FABRIC FILTER AIR-TO-CLOTH RATIO (FT/MIN)	LIME (LB/HR)	RECYCLE (LB/HR)
812	6131.	4713.	4276.	4263.	4751.	9.6	2.3	24.1	0.0
813	6042.	4699.	4306.	4280.	4523.	9.6	2.3	42.5	0.0
814	6059.	4774.	4441.	4413.	4552.	9.3	2.3	47.7	0.0
815	6073.	4657.	4287.	4261.	4474.	9.6	2.3	25.5	0.0
816	6235.	4764.	4246.	4226.	4425.	9.7	2.2	15.1	0.0
817	6095.	4728.	4166.	4146.	4441.	9.9	2.2	24.7	0.0
818	6058.	4699.	4193.	4161.	4364.	9.8	2.2	37.0	0.0
819	6058.	4663.	4165.	4139.	4348.	9.9	2.2	50.3	0.0
820	6208.	4821.	4317.	4283.	4448.	9.5	2.3	26.6	0.0
821	6066.	4593.	4261.	4241.	4388.	9.7	2.2	12.6	0.0
822	6081.	4600.	4137.	4112.	4347.	10.0	2.2	25.0	0.0
823	6051.	4635.	4139.	4120.	4308.	10.0	2.2	37.6	0.0
824	6095.	4660.	4136.	4116.	4285.	10.0	2.2	50.1	0.0
825	6193.	4660.	4168.	4162.	4473.	9.9	2.2	25.1	0.0
826	5965.	4729.	4351.	4338.	4540.	9.5	2.3	14.2	0.0
827	6058.	4669.	4293.	4266.	4508.	9.6	2.3	26.2	0.0
828	6162.	4671.	4174.	4155.	4543.	9.9	2.2	39.6	0.0
829	6125.	4667.	4241.	4221.	4444.	9.7	2.2	52.3	0.0
830	6131.	4744.	4299.	4273.	4529.	9.6	2.3	25.1	0.0
831	5960.	4706.	4157.	4125.	4471.	9.9	2.2	12.5	0.0
832	5996.	4729.	4105.	4086.	4407.	10.0	2.2	24.8	0.0
833	5996.	4710.	4211.	4176.	4415.	9.8	2.2	37.2	0.0
834	5965.	4722.	4225.	4199.	4256.	9.8	2.2	50.2	0.0
835	6033.	4770.	4316.	4296.	4463.	9.5	2.3	25.4	0.0
836	6051.	4665.	4171.	4139.	4242.	9.9	2.2	12.5	0.0

TABLE A.9. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

		SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL				
RUN (NO.)	RECYCLE RATIO $\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	INLET (LB/HR)	OUTLET (LB/HR)	OUTLET (LB/HR)	S.D. (PCT)	F.F. (PCT)	OVERALL (PCT)	STOICHIOMETRIC RATIO $\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	REAGENT UTILIZATION (PCT)
812	0.0	21.0	14.1	13.2	32.9	6.1	36.9	0.99	37.
813	0.0	21.8	12.7	11.0	42.0	13.0	49.5	1.68	29.
814	0.0	21.3	13.7	9.9	35.8	27.5	53.4	1.93	28.
815	0.0	23.1	17.3	15.8	25.1	8.6	31.5	0.96	33.
816	0.0	22.2	18.9	17.9	14.9	5.5	19.6	0.59	33.
817	0.0	22.2	15.0	13.3	32.3	11.4	40.0	0.96	42.
818	0.0	21.0	12.6	11.3	40.2	10.3	46.3	1.52	30.
819	0.0	19.9	11.4	9.7	42.7	15.0	51.3	2.18	24.
820	0.0	21.7	14.2	13.6	34.8	4.0	37.4	1.06	35.
821	0.0	21.5	17.5	16.8	18.6	3.9	21.7	0.50	43.
822	0.0	21.4	15.4	14.8	28.0	4.0	30.9	1.01	31.
823	0.0	21.6	14.1	12.4	34.5	12.3	42.6	1.51	28.
824	0.0	21.4	11.5	10.4	46.3	9.5	51.4	2.02	25.
825	0.0	20.5	13.2	12.8	35.4	3.5	37.7	1.06	36.
826	0.0	20.8	19.4	15.8	6.6	18.8	24.1	0.59	41.
827	0.0	21.3	14.7	13.3	30.8	9.8	37.6	1.06	35.
828	0.0	21.4	12.6	10.1	41.0	20.5	53.0	1.60	33.
829	0.0	21.5	11.9	9.3	44.6	22.2	57.0	2.10	27.
830	0.0	22.3	17.2	15.5	22.8	10.1	30.6	0.97	32.
831	0.0	22.7	18.8	19.1	17.0	-1.3	15.9	0.48	33.
832	0.0	22.4	14.0	14.2	37.7	-1.3	36.9	0.95	39.
833	0.0	21.7	13.3	11.8	38.9	11.2	45.8	1.48	31.
834	0.0	22.1	12.9	11.2	42.3	12.5	49.5	1.96	25.
835	0.0	23.2	15.0	14.4	35.4	3.9	37.9	0.95	40.
836	0.0	21.3	17.2	16.5	19.1	4.0	22.4	0.51	44.

TABLE A.10. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D. INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
837	0.0	0.0	790.	520.	440.	5.0	5.5	7.5	124.	119.
838	0.0	0.0	800.	500.	395.	6.2	7.1	8.2	126.	122.
839	0.0	0.0	840.	435.	330.	5.0	6.0	7.9	125.	120.
840	0.0	0.0	800.	530.	470.	5.0	5.5	7.0	122.	118.
906	1.2	23.3	790.	590.	510.	6.5	6.9	8.2	124.	119.
907	1.2	26.2	740.	540.	470.	6.5	6.9	8.2	125.	120.
907R	1.2	23.3	740.	460.	400.	5.4	5.8	7.0	120.	117.
908	1.2	26.2	760.	505.	435.	6.1	6.5	7.7	120.	116.
908R	1.2	23.3	760.	480.	410.	5.4	5.7	7.2	117.	113.
909	1.2	23.3	810.	420.	370.	5.4	5.7	7.2	130.	125.
910	0.0	0.0	830.	610.	540.	5.4	5.7	7.2	124.	119.
910A	1.2	26.2	820.	670.	580.	5.4	5.7	7.2	124.	119.
910B	1.2	23.3	800.	420.	340.	5.7	6.0	7.2	126.	122.
911	1.2	26.2	810.	270.	200.	5.7	6.0	7.2	123.	119.
911R	1.2	23.3	830.	330.	270.	5.3	5.7	7.4	126.	121.
912	1.2	26.2	750.	310.	210.	5.5	6.3	7.6	126.	122.
912R	1.2	26.2	790.	330.	300.	5.5	6.3	7.6	123.	119.
913	1.2	26.2	805.	410.	340.	5.8	6.0	7.9	126.	121.
914	1.2	23.3	820.	460.	410.	5.8	6.0	7.9	124.	119.
915R	1.2	26.2	850.	510.	440.	5.8	6.4	8.0	126.	121.
916	1.2	27.8	810.	520.	450.	5.4	5.8	7.2	120.	116.
917	1.2	27.8	780.	390.	280.	5.5	6.0	7.5	120.	116.
918	1.2	27.8	780.	340.	190.	5.2	6.0	7.5	124.	119.
919	1.2	27.8	780.	350.	300.	5.0	5.5	7.5	125.	119.
920	1.2	27.8	810.	310.	210.	5.5	6.0	8.0	124.	119.

TABLE A.10 SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLUW	LIME SLURRY			RECY.SLURRY
RUN (NO.)	INLET (DEG.F)	OUTLET (DEG.F)	INLET (DEG.F)	OLTLET (DEG.F)	INLET (DEG.F)	INITIAL ΔP (IN. WATER)	FLOW (GPM)	S.G.	$C_A(OH)_2$ (WT. PCT)	FLCW (GPM)
837	295.	174.	172.	154.	540.	0.83	0.38	1.07	12.1	0.0
838	302.	184.	182.	155.	537.	0.82	0.56	1.07	12.1	0.0
839	298.	176.	173.	148.	535.	0.74	0.76	1.07	12.1	0.0
840	308.	190.	187.	162.	545.	0.82	0.56	1.07	8.4	0.0
906	235.	176.	174.	145.	510.	1.10	0.25	1.11	15.5	0.37
907	239.	160.	155.	145.	535.	0.97	0.26	1.11	19.0	0.44
907R	233.	169.	166.	135.	520.	0.99	0.31	1.11	15.5	0.50
908	238.	156.	154.	135.	505.	0.96	0.39	1.11	19.0	0.66
908R	232.	169.	167.	135.	523.	0.98	0.40	1.11	15.5	0.63
909	340.	173.	170.	153.	505.	0.75	0.25	1.11	15.5	0.37
910	335.	161.	159.	135.	480.	0.78	0.26	1.11	19.0	0.0
910A	340.	174.	170.	144.	500.	0.77	0.26	1.11	19.0	0.39
910B	336.	171.	168.	137.	515.	0.75	0.28	1.11	15.5	0.43
911	328.	157.	153.	135.	520.	0.78	0.34	1.11	19.0	0.58
911R	333.	174.	170.	138.	520.	0.76	0.42	1.11	15.5	0.66
912	327.	173.	170.	148.	470.	0.75	0.42	1.11	19.0	0.25
912R	333.	162.	158.	152.	450.	0.75	0.25	1.11	19.0	0.42
913	321.	175.	172.	150.	470.	0.75	0.25	1.11	19.0	0.43
914	332.	185.	181.	147.	510.	0.75	0.29	1.11	15.5	0.45
915R	335.	206.	200.	160.	490.	0.71	0.25	1.11	19.0	0.42
916	230.	150.	147.	125.	530.	0.99	0.25	1.07	16.6	0.34
917	235.	155.	152.	130.	525.	0.98	0.25	1.13	19.8	0.43
918	243.	152.	146.	127.	530.	0.98	0.38	1.13	19.8	0.63
919	331.	155.	152.	136.	540.	0.75	0.25	1.07	16.6	0.30
920	338.	155.	152.	130.	515.	0.75	0.25	1.13	19.8	0.43

TABLE A.10. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE ENTER COOLER					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE LIME	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
837	6125.	4625.	4119.	4106.	4503.	10.0	2.2	24.8	0.0
838	6079.	4646.	4281.	4268.	4412.	9.6	2.3	36.6	0.0
839	5769.	4395.	4030.	4011.	4341.	10.2	2.1	49.6	0.0
840	6103.	4664.	4184.	4164.	4391.	9.9	2.2	25.0	0.0
906	6945.	4976.	4744.	4729.	4929.	8.7	2.5	21.6	51.7
907	6605.	4640.	4308.	4273.	4591.	9.6	2.3	27.5	69.1
907R	6622.	4683.	4425.	4404.	4516.	9.3	2.3	26.8	69.9
908	6471.	4681.	4323.	4309.	4522.	9.5	2.3	41.2	103.7
908R	6599.	4645.	4367.	4354.	4536.	9.4	2.3	34.5	88.1
909	5720.	4742.	3974.	3955.	4226.	10.4	2.1	21.6	51.7
910	5757.	4869.	4035.	4022.	4245.	10.2	2.1	27.5	0.0
910A	5780.	4817.	4043.	4017.	4229.	10.2	2.1	27.5	61.3
910B	5749.	4694.	3941.	3922.	4027.	10.5	2.1	24.2	60.1
911	5878.	4727.	3925.	3900.	4088.	10.5	2.1	35.9	91.1
911R	5802.	4695.	3993.	3968.	4185.	10.3	2.1	36.2	92.3
912	5615.	4752.	4165.	4145.	4354.	9.9	2.2	44.4	39.3
912R	5554.	4840.	4153.	4126.	4447.	9.9	2.2	26.4	66.0
913	5615.	4715.	4018.	3999.	4348.	10.3	2.1	26.4	67.6
914	5735.	4682.	3997.	3972.	4238.	10.3	2.1	25.0	62.9
915R	5572.	4621.	4146.	4108.	4282.	9.9	2.2	26.4	66.0
916	6656.	4639.	4285.	4264.	4488.	9.6	2.3	22.2	57.1
917	6606.	4661.	4337.	4316.	4577.	9.5	2.3	27.9	72.2
918	6622.	4703.	4393.	4350.	4635.	9.4	2.3	42.5	105.8
919	5823.	4606.	3846.	3827.	4208.	10.7	2.0	22.2	50.4
920	5744.	4705.	3904.	3885.	4245.	10.6	2.1	27.9	72.2

TABLE A.10. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } Ca(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } Ca(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
837	0.0	21.3	14.9	14.2	30.2	4.5	33.3	1.01	33.
838	0.0	21.4	14.6	12.5	31.9	14.7	41.9	1.47	28.
839	0.0	21.4	12.1	10.4	43.4	14.5	51.6	2.00	26.
840	0.0	21.4	15.0	14.6	29.8	2.7	31.7	1.01	31.
906	2.4	24.9	19.4	18.3	22.2	5.6	26.5	0.75	35.
907	2.5	21.6	16.5	15.7	23.6	4.9	27.4	1.10	25.
907R	2.6	22.0	14.2	13.4	35.3	6.2	39.3	1.05	37.
908	2.5	22.4	15.6	14.5	30.5	6.7	35.1	1.59	22.
908R	2.6	22.4	14.7	13.7	34.7	6.2	38.7	1.33	29.
909	2.4	21.1	11.6	11.2	45.1	3.3	46.9	0.88	53.
910	0.0	22.4	17.4	16.9	22.0	2.8	24.2	1.06	23.
910A	2.2	21.7	18.8	17.9	13.5	4.9	17.8	1.09	16.
910B	2.5	20.7	11.5	10.1	44.4	12.6	51.4	1.01	51.
911	2.5	21.4	7.6	6.0	64.6	20.0	71.7	1.45	49.
911R	2.5	21.6	9.1	8.3	57.7	9.1	61.5	1.45	42.
912	0.9	19.9	9.0	6.6	55.0	26.3	66.8	1.92	35.
912R	2.5	21.2	9.7	9.6	54.3	1.1	54.8	1.08	51.
913	2.6	21.4	11.4	10.7	46.6	6.6	50.1	1.07	47.
914	2.5	21.3	12.5	12.6	41.2	-0.4	41.0	1.01	40.
915R	2.5	21.7	14.0	13.4	35.7	4.3	38.5	1.05	37.
916	2.6	23.9	16.1	15.2	32.9	5.5	36.6	0.80	46.
917	2.6	23.0	12.1	9.6	47.4	21.0	58.5	1.05	56.
918	2.5	22.9	10.7	6.6	53.2	38.5	71.2	1.60	45.
919	2.3	20.0	9.6	9.3	51.8	3.2	53.4	0.96	55.
920	2.6	21.0	8.7	6.6	58.8	23.2	68.4	1.15	60.

TABLE A.11. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
921	1.2	27.8	800.	225.	105.	5.6	6.1	7.6	126.	122.
922	1.2	27.8	1460.	740.	600.	5.0	5.7	7.6	123.	118.
923	1.2	31.3	1380.	540.	300.	5.5	6.5	9.0	125.	119.
925	1.2	27.8	1520.	640.	500.	5.5	5.9	7.5	124.	115.
926	1.2	27.8	1390.	440.	270.	5.5	6.0	7.5	124.	119.
927	1.2	27.8	1360.	400.	220.	5.0	5.5	7.0	124.	119.
931	1.2	27.8	2000.	750.	520.	4.8	5.4	7.4	127.	122.
932	1.2	27.8	2050.	725.	480.	4.8	5.3	6.8	123.	119.
933	1.2	31.3	2100.	650.	450.	6.0	7.5	8.5	129.	125.
934	1.2	31.3	805.	600.	470.	5.5	6.0	8.0	125.	119.
935	1.2	31.3	810.	470.	400.	6.0	6.5	8.0	122.	118.
936	1.2	31.3	830.	480.	400.	6.0	6.5	8.0	121.	117.
937	1.2	31.3	750.	340.	290.	4.2	5.2	6.6	129.	125.
938	1.2	31.3	765.	365.	280.	4.2	5.2	6.6	123.	119.
939	1.2	31.3	800.	360.	270.	4.2	5.2	6.6	123.	119.
924	1.3	37.8	1560.	780.	680.	5.5	5.9	7.5	125.	118.
928	1.3	37.8	2000.	970.	760.	6.0	6.2	7.5	125.	118.
929	1.3	37.8	2040.	1160.	1000.	5.2	6.0	7.5	125.	118.
930	1.3	37.8	2000.	880.	640.	6.0	6.3	8.0	125.	118.
951	1.4	42.9	500.	140.	115.	7.0	7.5	9.0	117.	117.
951R	1.3	45.4	490.	115.	130.	7.0	7.5	9.0	111.	111.
952	1.4	42.9	510.	90.	130.	7.0	7.5	9.0	117.	****
952R	1.3	33.5	480.	85.	107.	7.0	7.5	9.0	111.	111.
953	1.4	41.1	510.	85.	115.	7.0	7.5	9.0	117.	117.
953A	1.4	41.1	520.	70.	120.	7.0	7.5	9.0	117.	117.

TABLE A.11. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY.SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
921	336.	151.	148.	130.	510.	0.73	0.33	1.13	19.8	0.53
922	239.	153.	150.	128.	550.	0.99	0.50	1.07	16.6	0.65
923	255.	147.	144.	131.	555.	0.98	0.64	1.04	15.9	0.72
925	329.	155.	153.	130.	530.	0.79	0.39	1.13	19.8	0.64
926	334.	152.	150.	130.	540.	0.76	0.46	1.13	19.8	0.72
927	339.	155.	152.	131.	540.	0.75	0.63	1.10	17.5	0.93
931	325.	152.	150.	134.	550.	0.75	0.51	1.15	20.2	0.90
932	326.	154.	152.	135.	545.	0.79	0.68	1.15	20.2	1.17
933	361.	157.	155.	135.	545.	0.81	1.10	1.10	15.9	1.22
934	258.	165.	160.	136.	550.	0.98	0.25	1.10	15.9	0.29
935	250.	168.	164.	136.	535.	0.92	0.29	1.10	19.0	0.30
936	251.	178.	175.	144.	555.	1.00	0.44	1.08	15.3	0.45
937	352.	170.	167.	147.	540.	0.78	0.25	1.08	15.3	0.27
938	354.	173.	170.	149.	540.	0.74	0.29	1.08	15.3	0.30
939	351.	169.	165.	151.	535.	0.75	0.44	1.08	15.3	0.45
924	248.	162.	158.	130.	540.	1.00	0.0	0.0	11.8	1.19
928	232.	148.	144.	126.	510.	0.96	0.0	0.0	11.8	0.82
929	232.	151.	148.	125.	525.	0.97	0.0	0.0	11.8	0.63
930	231.	145.	141.	125.	515.	1.00	0.0	0.0	11.8	0.98
951	275.	169.	204.	174.	460.	1.17	0.16	1.39	15.8	0.16
951R	272.	166.	202.	168.	400.	1.26	0.19	1.25	14.2	0.19
952	290.	154.	210.	174.	465.	1.44	0.14	1.39	15.8	0.14
952R	268.	154.	195.	150.	400.	1.46	0.15	1.26	12.2	0.15
953	271.	145.	208.	178.	460.	1.38	0.14	1.37	14.4	0.14
953A	261.	133.	198.	167.	450.	1.54	0.13	1.37	13.7	0.13

TABLE A.11. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	GAS FLOW RATE					SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	SLURRY FEED RATE	
	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.			LIME	RECYCLE
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
921	5658.	4643.	3839.	3821.	4081.	10.7	2.0	36.9	89.0
922	6723.	4653.	4345.	4324.	4685.	9.5	2.3	44.5	109.2
923	6705.	4724.	4377.	4355.	4997.	9.4	2.3	53.0	136.8
925	5946.	4739.	3944.	3931.	4184.	10.5	2.1	43.6	107.5
926	5861.	4654.	3861.	3849.	4095.	10.7	2.0	51.4	121.0
927	5823.	4652.	3852.	3834.	4060.	10.7	2.0	60.6	156.2
931	5852.	4548.	3827.	3814.	4190.	10.8	2.0	59.4	151.2
932	5991.	4685.	3925.	3913.	4167.	10.5	2.1	79.1	196.6
933	6066.	4955.	4293.	4279.	4447.	9.6	2.3	96.7	235.1
934	6689.	4755.	4366.	4331.	4719.	9.4	2.3	22.0	55.9
935	6433.	4590.	4276.	4249.	4478.	9.6	2.3	30.3	57.8
936	6774.	4745.	4475.	4454.	4675.	9.2	2.4	36.4	86.7
937	5938.	4822.	4133.	4113.	4335.	10.0	2.2	20.7	52.0
938	5784.	4708.	4044.	4025.	4235.	10.2	2.1	24.0	57.8
939	5808.	4734.	4057.	4031.	4290.	10.2	2.1	36.4	86.7
924	6723.	4760.	4376.	4348.	4591.	9.4	2.3	91.9	294.6
928	6487.	4628.	4202.	4174.	4406.	9.8	2.2	63.3	203.0
929	6571.	4617.	4364.	4343.	4596.	9.4	2.3	48.7	155.9
930	6638.	4705.	4286.	4258.	4624.	9.6	2.2	75.7	242.6
951	7045.	4744.	4434.	5400.	5740.	9.3	2.4	17.6	47.8
951R	7070.	4805.	4485.	5840.	6040.	9.2	2.6	16.8	53.9
952	7925.	4995.	4560.	6070.	6260.	9.0	2.7	15.4	41.8
952R	7600.	5130.	4740.	6230.	6425.	8.7	2.9	11.5	31.6
953	7655.	4775.	4340.	5995.	6240.	9.5	2.7	13.8	39.4
953A	8040.	4950.	4480.	6270.	6510.	9.2	2.8	12.2	36.9

TABLE A.11. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
921	2.4	20.5	6.2	3.2	69.7	48.6	84.4	1.55	54.
922	2.5	42.7	23.1	21.0	46.0	8.9	50.8	0.90	57.
923	2.6	49.1	17.1	11.2	57.3	34.9	72.2	1.14	63.
925	2.5	40.1	18.0	15.6	55.0	13.6	61.2	0.94	65.
926	2.4	35.8	12.2	8.2	65.9	32.5	77.0	1.24	62.
927	2.6	34.8	11.0	6.6	68.4	39.7	80.9	1.50	54.
931	2.5	50.9	20.6	16.1	59.5	21.8	68.3	1.01	68.
932	2.5	53.7	20.4	14.8	62.1	27.5	72.5	1.27	57.
933	2.4	55.7	19.9	14.8	64.3	25.6	73.5	1.50	49.
934	2.5	23.4	18.4	16.4	21.4	11.2	30.2	0.81	37.
935	1.9	23.0	14.1	13.2	38.9	6.1	42.6	1.14	37.
936	2.4	24.4	14.8	13.6	39.2	8.0	44.1	1.29	34.
937	2.5	19.6	9.8	9.1	49.9	7.1	53.5	0.91	59.
938	2.4	19.5	10.3	8.6	47.3	16.5	56.0	1.07	53.
939	2.4	20.5	10.2	8.3	50.3	18.4	59.4	1.53	39.
924	2.2	46.1	24.1	23.2	47.6	3.5	49.5	1.72	29.
928	2.2	58.8	27.9	25.1	52.4	10.1	57.2	0.93	62.
929	2.2	59.8	36.4	34.5	39.1	5.1	42.2	0.70	60.
930	2.2	59.8	27.4	22.2	54.2	18.8	62.8	1.09	58.
951	1.7	13.6	4.2	4.4	69.4	15.7	70.2	1.12	63.
951R	2.2	13.6	3.5	5.3	74.4	0.0	64.7	1.07	61.
952	1.7	14.5	2.8	5.4	80.6	0.0	65.9	0.92	72.
952R	1.8	14.3	2.8	4.7	80.6	0.0	70.4	0.70	***
953	1.9	14.0	2.6	4.7	81.6	0.0	69.5	0.85	82.
953A	2.0	15.1	2.2	5.3	85.2	0.0	68.6	0.70	98.

TABLE A.12. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.INLET	S.D.OUTLET	F.F.OUTLET	S.D.OUTLET	F.F.OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG.F)	(DEG.F)
954	1.3	38.8	265.	80.	85.	7.0	7.5	9.0	117.	117.
954R	1.3	45.4	200.	50.	65.	7.0	7.5	9.0	111.	111.
955	1.3	38.8	245.	60.	55.	7.0	7.5	9.0	117.	117.
956	1.3	38.8	260.	30.	65.	7.0	7.5	9.0	117.	117.
956R	1.3	45.4	200.	25.	55.	7.0	7.5	9.0	111.	111.
957	1.4	41.1	480.	120.	130.	7.0	7.5	9.0	117.	117.
958	1.3	36.5	200.	35.	65.	7.0	7.5	9.0	117.	117.
959	0.0	0.0	530.	105.	110.	7.0	7.5	9.0	117.	117.
960	0.0	0.0	530.	120.	130.	7.0	7.5	9.0	117.	117.
961	0.0	0.0	500.	60.	65.	7.0	7.5	9.0	117.	117.
962	0.0	0.0	530.	50.	70.	7.0	7.5	9.0	117.	117.
963	0.0	0.0	280.	75.	70.	7.0	7.5	9.0	117.	117.
964	0.0	0.0	250.	50.	55.	7.0	7.5	9.0	117.	117.
965	0.0	0.0	315.	20.	50.	7.0	7.5	9.0	117.	117.
966	0.0	0.0	200.	20.	25.	7.0	7.5	9.0	117.	117.
967	1.4	41.1	520.	60.	60.	7.0	7.5	9.0	117.	117.
968	1.4	41.1	450.	75.	75.	7.0	7.5	9.0	117.	117.
969	1.2	32.0	185.	30.	25.	7.0	7.5	9.0	117.	117.
970	1.3	36.5	200.	30.	50.	7.0	7.5	9.0	117.	117.
970R	1.3	45.4	200.	25.	30.	7.0	7.5	9.0	111.	111.
971	1.4	42.6	505.	35.	20.	7.0	7.5	9.0	117.	117.
972	1.2	32.4	185.	40.	17.	7.0	7.5	9.0	117.	117.

TABLE A.12. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECY. SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL △P	FLOW	S.G.	$C_A(OH)_2$	FLOW
(NO.)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(DEG.F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
954	274.	166.	200.	162.	400.	1.28	0.16	1.29	12.5	0.16
954R	267.	164.	202.	172.	460.	1.21	0.13	1.25	14.2	0.13
955	274.	156.	202.	168.	460.	1.33	0.14	1.29	12.5	0.14
956	272.	145.	203.	167.	480.	1.50	0.29	1.29	12.5	0.29
956R	276.	146.	199.	172.	400.	1.30	0.10	1.25	14.2	0.10
957	236.	147.	200.	167.	460.	1.56	0.24	1.37	13.8	0.24
958	236.	146.	200.	166.	460.	1.58	0.27	1.28	12.7	0.27
959	269.	145.	189.	168.	500.	1.25	0.29	1.10	17.2	0.0
960	226.	140.	185.	160.	500.	1.62	0.43	1.11	17.3	0.0
961	273.	137.	188.	170.	490.	1.26	0.55	1.10	17.2	0.0
962	229.	128.	176.	153.	500.	1.56	0.80	1.11	17.3	0.0
963	269.	157.	205.	175.	510.	1.25	0.57	1.10	16.4	0.0
964	229.	136.	182.	162.	510.	1.48	0.55	1.10	17.2	0.0
965	263.	140.	192.	166.	560.	1.26	0.55	1.10	16.4	0.0
966	232.	134.	182.	162.	520.	1.54	0.16	1.11	17.3	0.0
967	271.	145.	204.	168.	450.	1.48	0.65	1.37	13.8	0.65
968	235.	145.	204.	171.	470.	1.60	0.65	1.37	13.8	0.65
969	267.	143.	174.	145.	420.	1.11	0.29	1.22	11.7	0.29
970	237.	146.	198.	166.	460.	1.58	0.43	1.28	12.7	0.43
970R	234.	144.	166.	155.	410.	1.55	0.28	1.25	14.2	0.28
971	275.	145.	172.	149.	450.	1.08	1.10	1.35	13.7	1.10
972	275.	155.	167.	135.	465.	1.04	0.54	1.22	11.7	0.54

TABLE A.12. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE								
RUN (NO.)	ENTER COOLER (ACFM)	ENTER S.D. (ACFM)	EXIT S.D. (ACFM)	ENTER F.F. (ACFM)	EXIT F.F. (ACFM)	SPRAY DRYER RESIDENCE TIME (SEC)	FABRIC FILTER AIR-TO-CLOTH RATIO (FT/MIN)	SLURRY FEED RATE LIME (LB/HR)	SLURRY FEED RATE RECYCLE (LB/HR)
954	7430.	5080.	4735.	5635.	5825.	8.7	2.5	12.9	40.2
954R	6930.	4660.	4365.	5700.	5950.	9.4	2.5	11.5	36.9
955	7515.	4900.	4510.	5835.	6030.	9.1	2.6	11.3	35.0
956	8065.	5035.	4580.	6145.	6335.	9.0	2.7	23.3	72.6
956R	7180.	4650.	4220.	5925.	6195.	9.8	2.6	8.9	28.4
957	8135.	4920.	4660.	6235.	6455.	8.9	2.8	22.5	67.1
958	8190.	4970.	4700.	6280.	6490.	8.8	2.8	22.0	63.1
959	7440.	4840.	4415.	5460.	5755.	9.3	2.4	27.5	0.0
960	8470.	5180.	4915.	6100.	6390.	8.4	2.7	41.3	0.0
961	7420.	4830.	4345.	5520.	5850.	9.5	2.4	52.2	0.0
962	8310.	5100.	4745.	5930.	6230.	8.7	2.6	76.8	0.0
963	7480.	4730.	4380.	5535.	5750.	9.4	2.4	51.4	0.0
964	8140.	4990.	4690.	5790.	6115.	8.8	2.6	52.2	0.0
965	7455.	4700.	4290.	5480.	5740.	9.6	2.4	49.1	0.0
966	8345.	5075.	4745.	5885.	6215.	8.7	2.6	15.4	0.0
967	7855.	4880.	4445.	6175.	6365.	9.3	2.7	61.0	182.3
968	8285.	4890.	4620.	6315.	6540.	8.9	2.8	61.0	182.3
969	6940.	4670.	4620.	5085.	5290.	9.7	2.2	20.7	57.3
970	8190.	4985.	4705.	6260.	6495.	8.8	2.8	35.0	100.5
970R	7890.	5590.	5285.	6110.	6540.	7.8	2.7	16.0	51.1
971	6730.	4725.	4285.	5090.	5345.	9.6	2.3	99.9	316.3
972	6660.	4890.	4490.	4920.	5090.	9.2	2.2	38.6	106.7

TABLE A.12. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	RECYCLE RATIO	SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL			STOICHIOMETRIC RATIO	REAGENT UTILIZATION
		INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL		
(NO.)	$\left(\frac{\text{LBS. RECYCLE}}{\text{LB. FRESH } C_A(OH)_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES } C_A(OH)_2}{\text{MOLES } SO_2 \text{ FED}}\right)$	(PCT)
954	2.1	7.7	2.6	3.4	67.0	9.2	62.2	1.44	43.
954R	2.2	5.4	1.5	2.6	72.7	9.6	62.0	1.84	34.
955	2.1	6.9	1.9	2.2	73.1	34.3	73.6	1.40	52.
956	2.1	7.6	1.0	2.8	87.3	2.0	70.6	2.67	27.
956R	2.2	5.3	0.7	2.3	86.2	7.1	67.7	1.44	47.
957	2.0	14.3	3.9	5.7	72.9	0.0	64.3	1.35	47.
958	1.9	6.0	1.2	2.8	81.0	0.0	62.0	3.15	20.
959	0.0	14.9	3.2	4.3	78.2	3.4	73.4	1.60	46.
960	0.9	16.9	4.2	5.7	75.5	0.0	69.0	2.10	33.
961	0.0	13.9	1.9	2.6	86.7	19.3	83.3	3.24	26.
962	0.0	16.6	1.7	3.0	89.7	0.7	83.2	4.00	21.
963	0.0	7.7	2.3	3.7	70.7	0.3	70.6	5.80	12.
964	0.0	7.6	1.7	2.3	78.3	20.6	74.2	5.90	13.
965	0.0	8.7	0.6	1.9	93.0	15.2	81.3	4.90	17.
966	0.0	6.2	0.7	1.1	89.0	37.0	85.3	2.14	40.
967	2.0	14.7	1.9	2.6	87.3	26.8	84.3	3.59	24.
968	2.0	13.4	2.4	3.3	81.9	17.9	78.0	3.94	20.
969	1.8	5.0	0.9	0.9	82.2	43.7	64.0	3.57	24.
970	1.9	6.0	1.0	2.2	83.7	11.0	70.9	5.00	14.
970R	2.2	6.8	0.9	1.4	86.4	24.0	82.4	3.14	41.
971	2.1	13.7	1.0	0.7	92.4	60.3	94.9	6.40	15.
972	1.8	5.2	1.2	0.6	76.3	63.0	89.0	6.40	14.

TABLE A.13. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

RUN	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			FLYASH SLURRY
	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	Ca(OH)2	FLOW
(NO.)	(DEG. F)	(DEG. F)	(DEG. F)	(DEG. F)	(DEG. F)	(IN. WATER)	(GPM)		(WT. PCT)	(GPM)
701	291	186	181	148	470	0.81	0	0	0	0.78
702	305	183	179	147	500	0.76	0	0	0	0.60
703	297	178	173	143	470	0.81	0	0	0	0.69
704	298	179	171	143	540	0.83	0	0	0	0.28
705	310	192	183	150	510	0.81	0	0	0	0.55
706	304	185	181	152	525	0.77	0	0	0	0.70
707	299	187	183	143	515	0.79	0	0	0	0.67
708	300	179	175	145	505	0.79	0	0	0	0.25
709	303	181	178	155	530	0.77	0	0	0	0.50
710	306	185	181	158	530	0.80	0	0	0	0.80
711	308	192	183	150	530	0.82	0	0	0	0.78

TABLE A.13. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

RUN	FLYASH SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
	S.G.	SOLIDS	S.D. INLET	S.D. OUTLET	F.F. OUTLET	S.D. INLET	S.D. OUTLET	F.F. OUTLET	S.D. OUTLET	F.F. OUTLET
(NO.)		(WT. PCT)	(PPMV)	(PPMV)	(PPMV)	(VOL. PCT)	(VOL. PCT)	(VOL. PCT)	(DEG. F)	(DEG. F)
701	1.24	36.5	770	530	450	3.0	4.0	5.5	124	120
702	1.24	36.5	760	500	435	3.0	4.0	5.5	124	120
703	1.13	24.9	760	555	490	3.0	3.7	5.0	124	120
704	1.13	24.9	800	680	560	3.0	3.7	5.0	124	120
705	1.13	24.9	800	610	540	3.0	3.7	5.0	125	120
706	1.23	29.9	715	535	430	3.0	3.7	5.0	124	120
707	1.18	24.7	730	610	500	3.0	3.3	4.0	121	119
708	1.18	24.7	735	620	530	3.0	3.5	4.7	122	119
709	1.19	27.3	760	575	500	3.0	3.7	5.0	126	119
710	1.19	27.3	750	535	440	3.0	3.7	5.0	126	122
711	1.34	65.4	850	620	490	3.0	3.7	5.0	128	124

TABLE A.13. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE							SLURRY FEED RATE	
RUN	ENTER COOLER	ENTER S.D.	EXIT S.D.	ENTER F.F.	EXIT F.F.	SPRAY DRYER RESIDENCE TIME	FABRIC FILTER AIR-TO-CLOTH RATIO	LIME	FLYASH
(NO.)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(ACFM)	(SEC)	(FT/MIN)	(LB/HR)	(LB/HR)
701	6475	5230	4940	4900	5060	8.3	2.6	0	177
702	6435	5130	4760	4730	4890	5.7	2.5	0	136
703	6470	5265	4765	4730	4895	8.6	2.5	0	97
704	7040	5335	4820	4770	4950	8.5	2.5	0	39
705	6690	5310	4835	4765	5065	8.5	2.5	0	77
706	6650	5160	4680	4655	4825	8.8	2.5	0	129
707	6685	5205	4755	4725	4560	8.7	2.5	0	98
708	6615	5210	4760	4730	4770	8.7	2.5	0	36
709	6670	5140	4640	4620	4835	8.9	2.4	0	91
710	6805	5265	5050	5020	5225	8.2	2.7	0	130
711	6875	5335	5015	4980	5185	8.2	2.6	0	342

TABLE A.13. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

		SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL				
RUN (NO.)	RECYCLE RATIO $\left(\frac{\text{LBS RECYCLE}}{\text{LB FRESH Ca(OH)}_2}\right)$	INLET (LB/HR)	OUTLET (LB/HR)	OUTLET (LB/HR)	S.D. (PCT)	F.F. (PCT)	OVERALL (PCT)	AVAILABLE STOICHIOMETRIC RATIO $\left(\frac{\text{MOLES SORBENT}}{\text{MOLES SO}_2\text{ FED}}\right)$	REAGENT UTILIZATION (PCT)
701	N.A.*	23.6	17.8	16.5	24.4	7.6	30.2	1.78	17.0
702	N.A.	22.4	16.3	15.4	27.3	5.3	31.2	1.44	21.7
703	N.A.	23.2	18.2	17.5	21.6	4.0	24.8	1.00	24.8
704	N.A.	24.7	22.6	20.2	8.7	10.6	18.3	0.38	48.2
705	N.A.	24.3	19.9	19.7	18.0	1.0	18.7	0.76	24.6
706	N.A.	21.2	17.1	14.9	19.5	12.7	29.7	1.44	20.6
707	N.A.	22.0	19.7	16.6	10.5	15.6	24.5	1.05	23.3
708	N.A.	22.2	20.3	18.4	8.3	9.6	17.1	0.39	43.8
709	N.A.	22.5	18.3	17.3	18.6	5.6	23.2	0.96	24.2
710	N.A.	22.7	18.4	16.4	18.7	11.3	27.8	1.27	22.0
711	N.A.	26.0	21.0	17.9	19.2	14.8	31.0	3.12	10.0

*Not Applicable

TABLE A.14. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS

	RECYCLE SLURRY		SO_2 CONCENTRATION			OXYGEN CONCENTRATION			ADIA. SAT. TEMP.	
RUN (NO.)	S.G.	SOLIDS (WT. PCT)	S.D. INLET (PPMV)	S.D. OUTLET (PPMV)	F.F. OUTLET (PPMV)	S.D. INLET (VOL. PCT)	S.D. OUTLET (VOL. PCT)	F.F. OUTLET (VOL. PCT)	S.D. OUTLET (DEG. F)	F.F. OUTLET (DEG. F)
901	1.21	29.4	800	710	650	6.6	6.9	8.2	123	119
901R	1.23	31.3	790	720	640	6.5	7.5	8.5	124	120
902	1.21	29.4	810	680	600	6.6	7.0	8.2	124	120
903	1.21	29.4	790	650	550	6.0	6.6	8.2	125	120
903R	1.23	31.3	790	665	590	6.5	7.0	8.5	125	120
904	1.21	29.4	760	610	510	6.0	6.6	8.2	123	118
905	1.21	29.4	820	620	530	6.0	6.6	8.2	123	118
905R	1.23	31.4	820	610	520	6.5	7.0	8.5	124	120

TABLE A.14. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	SPRAY DRYER TEMP.		FABRIC FILTER TEMP.		COOLER TEMP.	GAS FLOW	LIME SLURRY			RECYCLE SLURRY
RUN	INLET	OUTLET	INLET	OUTLET	INLET	INITIAL ΔP	FLOW	S.G.	$Ca(OH)_2$	FLOW
(NO.)	(DEG. F)	(DEG. F)	(DEG. F)	(DEG. F)	(DEG. F)	(IN. WATER)	(GPM)		(WT. PECT)	(GPM)
901	302	183	180	153	520	0.81	0	0	0	0.25
901R	304	177	175	144	545	0.83	0	0	0	0.25
902	304	182	179	151	545	0.82	0	0	0	0.39
903	312	193	187	154	540	0.84	0	0	0	0.56
903R	306	187	185	144	550	0.84	0	0	0	0.52
904	310	196	190	156	550	0.83	0	0	0	0.73
905	312	196	193	156	520	0.81	0	0	0	0.85
905R	305	185	182	146	550	0.84	0	0	0	0.84

TABLE A.14. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

	GAS FLOW RATE							SLURRY FEED RATE	
RUN (NO.)	ENTER COOLER (ACFM)	ENTER S.D. (ACFM)	EXIT S.D. (ACFM)	ENTER F.F. (ACFM)	EXIT F.F. (ACFM)	SPRAY DRYER RESIDENCE TIME (SEC)	FABRIC FILTER AIR-TO-CLOTH RATIO (FT/MIN)	LIME (LB/HR)	RECYCLE (LB/HR)
901	6790	5280	4755	4735	4950	8.7	2.5	0	44
901R	7045	5355	5030	5015	5085	8.2	2.7	0	48
902	7000	5320	4805	4790	4990	8.6	2.5	0	69
903	7015	5415	4975	4930	5200	8.3	2.6	0	100
903R	7115	5395	4950	4930	5135	8.3	2.6	0	100
904	7050	5375	4965	4935	5180	8.3	2.6	0	130
905	6745	5315	4905	4875	5120	8.4	2.6	0	151
905R	7115	5390	4880	4850	5010	8.4	2.6	0	162

TABLE A.14. SPRAY DRYER/FABRIC FILTER PILOT TEST RESULTS (CONT.)

		SPRAY DRYER SO_2 FLOW RATE		FABRIC FILTER SO_2 FLOW RATE	SO_2 REMOVAL				
RUN	RECYCLE RATIO	INLET	OUTLET	OUTLET	S.D.	F.F.	OVERALL	AVAILABLE STOICHIOMETRIC RATIO	REAGENT UTILIZATION
(NO.)	$\left(\frac{\text{LBS RECYCLE}}{\text{LB FRESH Ca(OH)}_2}\right)$	(LB/HR)	(LB/HR)	(LB/HR)	(PCT)	(PCT)	(PCT)	$\left(\frac{\text{MOLES SORBENT}}{\text{MOLES SO}_2\text{ FED}}\right)$	(PCT)
901	N.A.*	24.4	23.1	23.1	5.3	0	5.3	0.35	15.0
901R	N.A.	24.3	24.0	23.7	1.2	4.6	5.7	0.38	15.0
902	N.A.	24.8	22.4	21.6	9.8	3.6	13.0	0.53	24.5
903	N.A.	24.4	21.8	20.5	10.6	6.0	16.0	0.78	20.5
903R	N.A.	24.5	22.4	22.1	8.5	1.4	10.0	0.78	12.8
904	N.A.	23.3	20.3	18.9	13.0	7.0	19.0	1.07	17.7
905	N.A.	24.8	20.4	19.4	18.0	5.0	22.0	1.16	19.0
905R	N.A.	25.4	20.3	18.9	20.0	7.0	25.6	1.22	21.0

*Not Applicable

APPENDIX B

CHEMICAL AND PHYSICAL ANALYSES

COAL

Unit No. 2 at the Comanche Station burns a low sulfur, sub-bituminous coal from the Powder River Basin. Tables B.1 and B.2 give the proximate analysis and ultimate analysis, respectively, of a representative coal sample taken about midway through the test program. As shown, the typical sulfur content is 0.35 percent (as received basis) with a heating value of approximately 8500 Btu/lb Sampling and analyses were conducted by Public Service of Colorado. The coal typically contains approximately 5 percent ash on as received basis.

TABLE B.1 COMANCHE COAL PROXIMATE ANALYSIS (UNIT No. 2)

	As Received (Weight Percent)	Dry Basis (Weight Percent)
Moisture	27.32	-
Ash	4.82	6.63
Volatile Matter	33.32	45.85
Fixed Carbon	34.54	47.52
Total	100.00	100.00
Heating Value (higher), Btu/lb	8484	11673
Sulfur, %	0.35	0.48
Mineral Matter Free, Btu/lb		12584

TABLE B.2 COMANCHE COAL ULTIMATE ANALYSIS (UNIT No. 2)

	As Received (Weight Percent)	Dry Basis (Weight Percent)
Moisture	27.32	-
Carbon	49.16	67.64
Hydrogen	3.77	5.19
Nitrogen	0.72	0.99
Sulfur	0.35	0.48
Ash	4.82	6.63
Oxygen (Difference)	13.86	19.07
	100.00	100.00

FLY ASH

Mineral analyses of six fly ash samples collected in different months of the test program are presented in Table B.3. The mineral analyses were performed in the Research-Cottrell analytical labs. Comanche fly ash is highly alkaline with the CaO content in the range of 26 to 34 percent. MgO content ranges from 3.5 to 4.5 percent, Na_2O content from 1 to 5 percent, and K_2O content from 0.2 to 1.5 percent. The potential available alkalinity of the fly ash ranges from 0.47 to 0.53 moles per 100 lb of fly ash. Available alkalinity, in this case, is defined as moles of $CaO + MgO + Na_2O + K_2O - SO_3$ per 100 lb of fly ash.

TABLE B.3 COMANCHE FLYASH MINERAL ANALYSIS

(Weight Percent)

	Date of Sample					
Constituent	Nov. 1980	Oct. 1980	Sept. 1980	Aug. 1980	July 1980	June 1980
SiO_2	38.14	29.33	30.69	33.83	33.54	32.43
Al_2O_3	19.13	13.90	16.49	14.62	16.60	16.38
TiO_2	1.80	1.20	1.69	1.20	1.41	1.52
Fe_2O_3	5.28	5.39	5.49	4.48	5.56	5.51
CaO	26.65	33.72	29.08	29.11	27.79	32.41
MgO	4.09	3.58	4.50	4.41	4.28	4.07
Na_2O	2.57	1.41	3.44	4.60	3.66	3.05
K_2O	1.47	0.25	0.33	0.28	0.33	0.24
SO_3	1.68	5.10	4.60	4.71	6.35	5.00
P_2O_5	0.97	1.22	1.41	0.60	1.04	1.31
LOI	0.17	2.88	0.80	3.37	0.79	0.33
Undetermined	-	2.02	1.48	-	-	6.97
Total	101.95	97.98	98.52	101.21	101.31	93.03

The Comanche fly ash is cementitious in nature. Wet fly ash has a tendency to set up upon drying and can cause problems in slurry-handling, bag blinding, and bridging of the discharge hoppers. This type of fly ash is difficult to deal with when there is moisture present and care must be taken to assure smooth, continuous system operation.

Figure B-1 presents the particle size distribution of a typical sample of

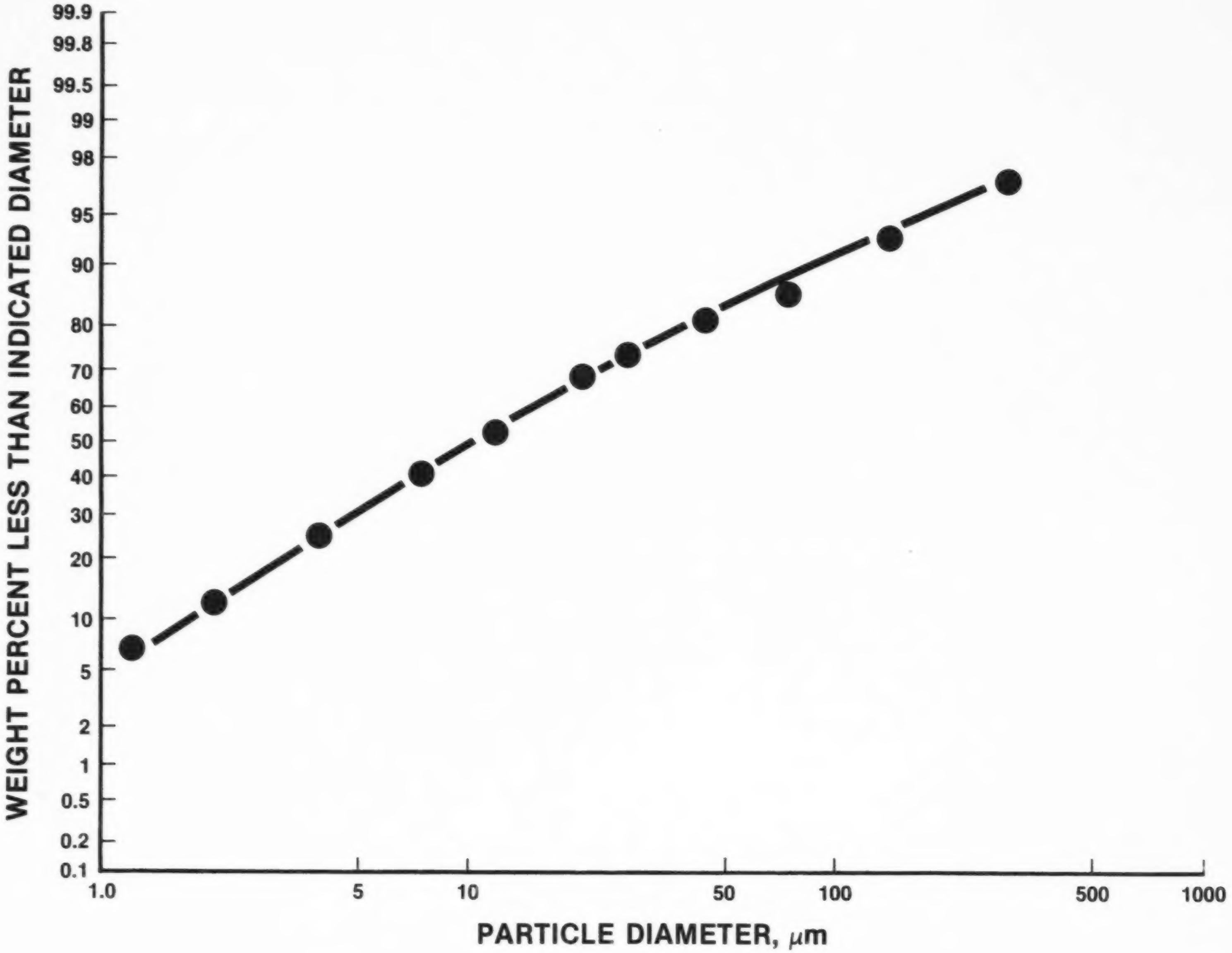

Figure B-1. Comanche Fly Ash Particle Size Distribution.

Comanche fly ash. Particle size distribution was determined in the Research-Cottrell analytical laboratory using physical sieve screening and the BAHCO technique. As shown in Table B.4, the particle size distribution of the fly ash was relatively consistent from month to month during the pilot test program. The mean particle diameter of the fly ash is in the range of 10 to 11 µm and 90 percent is typically less than 100 µm.

TABLE B.4 COMANCHE FLY ASH PARTICLE SIZE DISTRIBUTION

Sample Date	Mean Particle Diameter (µm)	Geometric Standard Deviation (µm)
June, 1980	10.4	3.71
August, 1980	14.3	3.33
September, 1980	12.2	3.94
October, 1980	6.6	3.03
November, 1980	10.0	3.85
Average of 5 samples	10.7	3.57

LIME

Essentially all of the test program was conducted using quicklime supplied by the Ash Grove Cement Company. Table B.5 presents a typical analysis of this Calmax quicklime. The analysis was provided by the Ash Grove Cement Company.

TABLE B.5 ASH GROVE QUICKLIME TYPICAL ANALYSIS

Component	Wt.%
Total Calcium Oxide (CaO)	95.75
Silicon Dioxide (SiO_2)	0.85
Ferric Oxide (Fe_2O_3)	0.07
Aluminum Oxide (Al_2O_3)	0.32
Phosphorous Pentoxide (P_2O_5)	0.02
Manganese Dioxide (MnO_2)	0.04
Titanium Dioxide (TiO_2)	0.05
Alkalies (combined) as (Na_2O)	0.03
Magnesium Oxide (MgO)	0.35
Sulfur Trioxide (SO_3)	0.01
Carbon Dioxide (CO_2)	0.37
Arsenic (As)	Less than 1 ppm
Fluorine (F)	Less than 50 ppm
Lead (Pb)	Less than 5 ppm
Specific Gravity	3.2 to 3.4
Specific Heat	0.19 BTU/lb
Bulk Density	52-55 lbs./cu. ft.

A typical particle size distribution for slaked Ash Grove Calmax quicklime is presented in Figure B-2. The particle size distribution was obtained by Structure-Probe, Inc. using a light scattering method (Quantimet).

A correlation was developed between specific gravity of the hydrated lime slurry and its $Ca(OH)_2$ content (Figure B-3). The analyses were conducted in the field test lab at the Comanche site. Although the two parameters correlate well, the plot was used only as checkpoint during the pilot plant tests and not for calculation purposes. The data used for process calculations were the actual results of analytical determinations that were performed on each individual batch of slaked lime. Specific gravity was determined by gravimetric analysis of a known volume of sample.

RECYCLE SOLIDS SLURRY

The analysis of feed material (fresh lime plus recycle) to the spray dryer is determined from a chemical analysis of the product solids prior to reslurrying along with the slurry concentrations and flow rates. Figure B-4 presents a correlation of specific gravity versus total solids content of the recycle solids. As with the fresh lime slurry correlation, the recycle solids correlation curve was used only as a checkpoint for the pilot test runs and not for process calculations. Process calculations were based on the results of analytical determinations performed on each individual batch. Specific gravity was determined by gravimetric analysis of a known volume of sample, and the total solids content was obtained from weighing using an Ohaus balance.

DILUTION WATER

A series of tests was conducted in which normal plant process water was used for slaking and as trim water, but a synthetically-doped, aqueous solution was used for slurry makeup and dilution water (Runs 951-972). Table B.6 gives the chemical composition of this synthetic solution.

TABLE B.6 DOPED DILUTION WATER COMPOSITION

Constituent	Value
Ca, ppm as $CaCO_3$	82
Mg, ppm as $CaCO_3$	432
Na, ppm as $CaCO_3$	24,520
SO_4, ppm as $CaCO_3$	21,200
Cl, ppm as $CaCO_3$	2,080
CO_3 ppm as $CaCO_3$	193
K, ppm as $CaCO_3$	9
TDS, ppm	41,920
TSS, ppm	525
pH	9.1

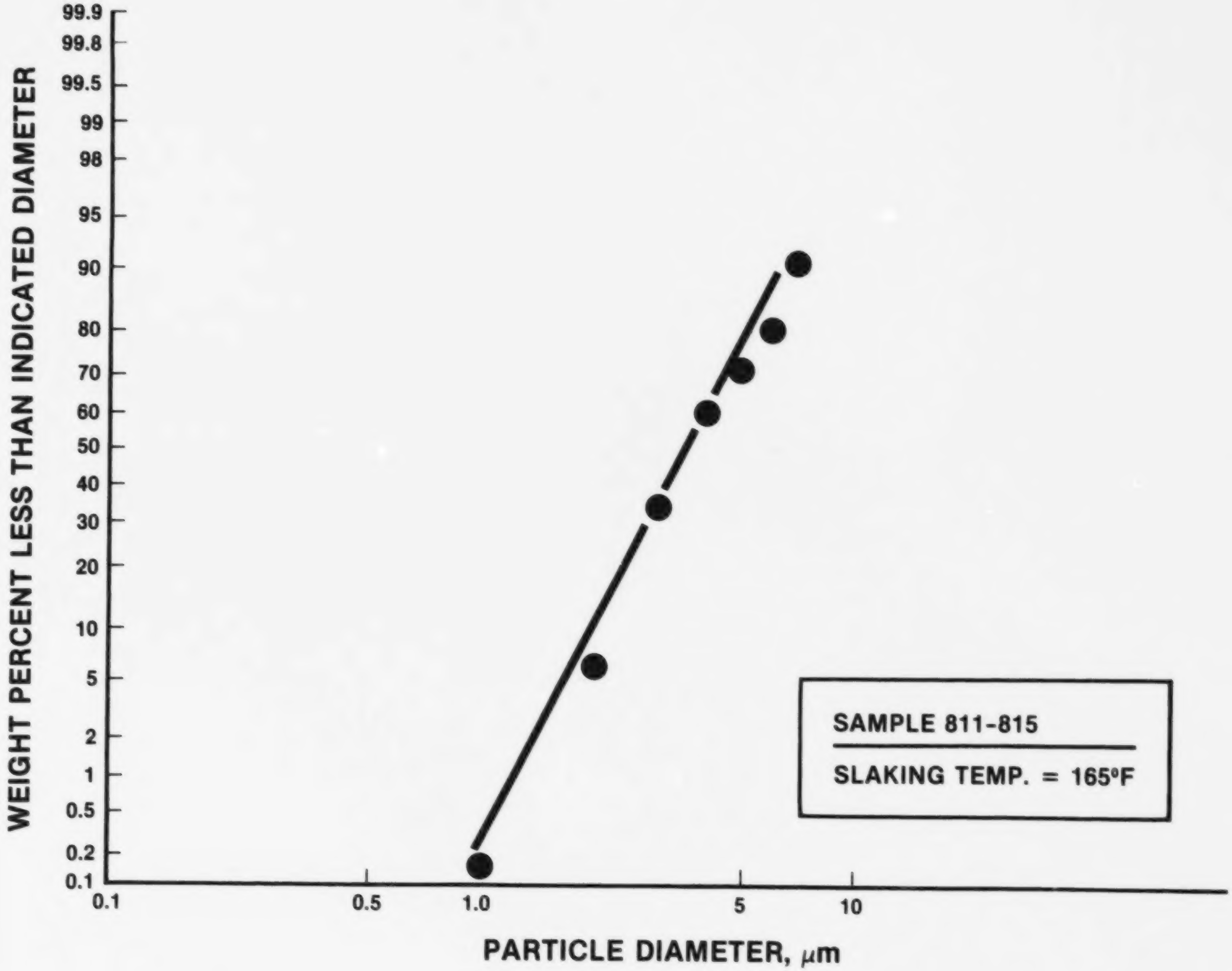

Figure B-2. Ash Grove Slaked Lime Particle Size Distribution.

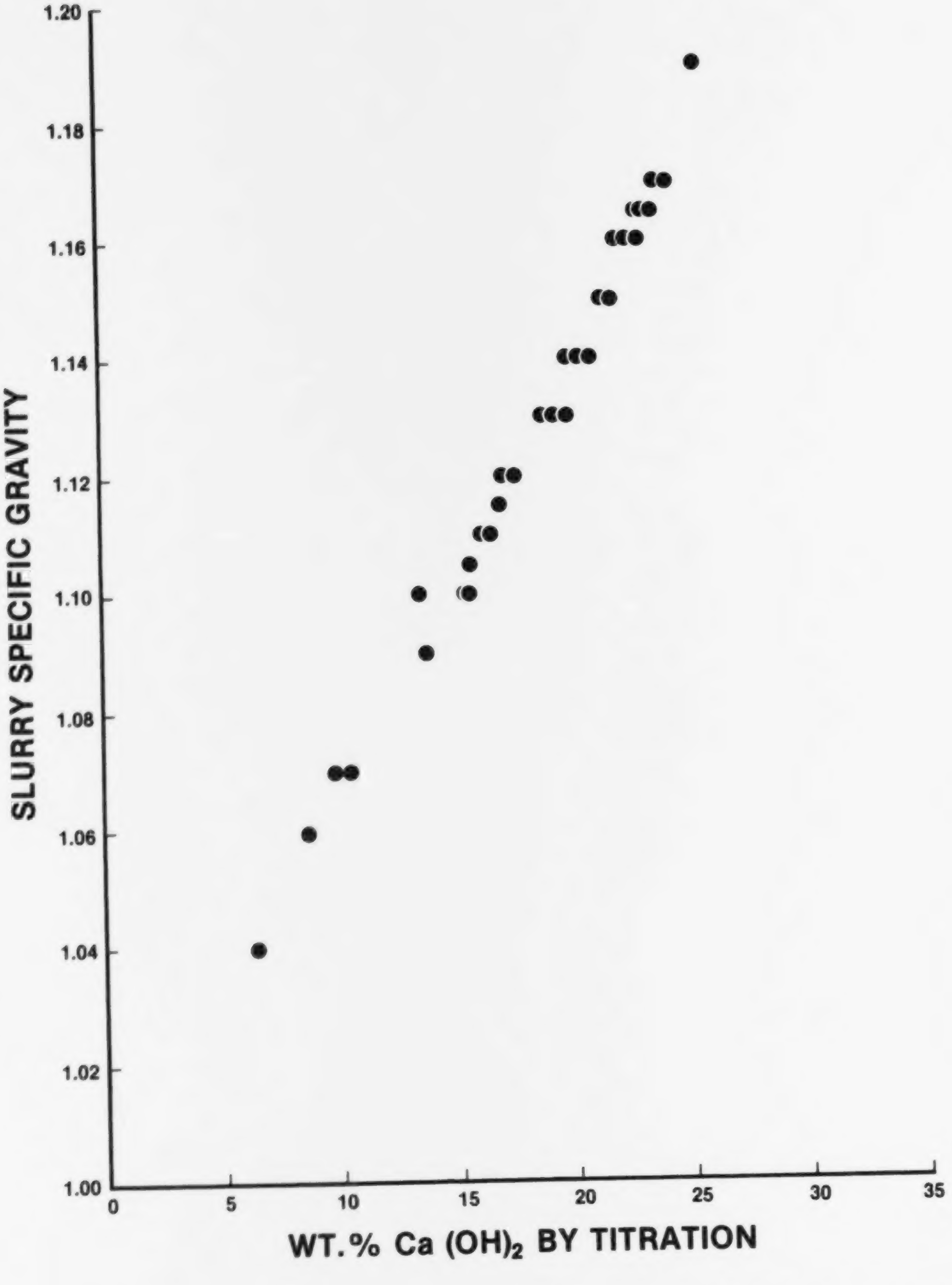

Figure B-3. Ash Grove Lime Slurry Specific Gravity Dependence on Ca $(OH)_2$ Content.

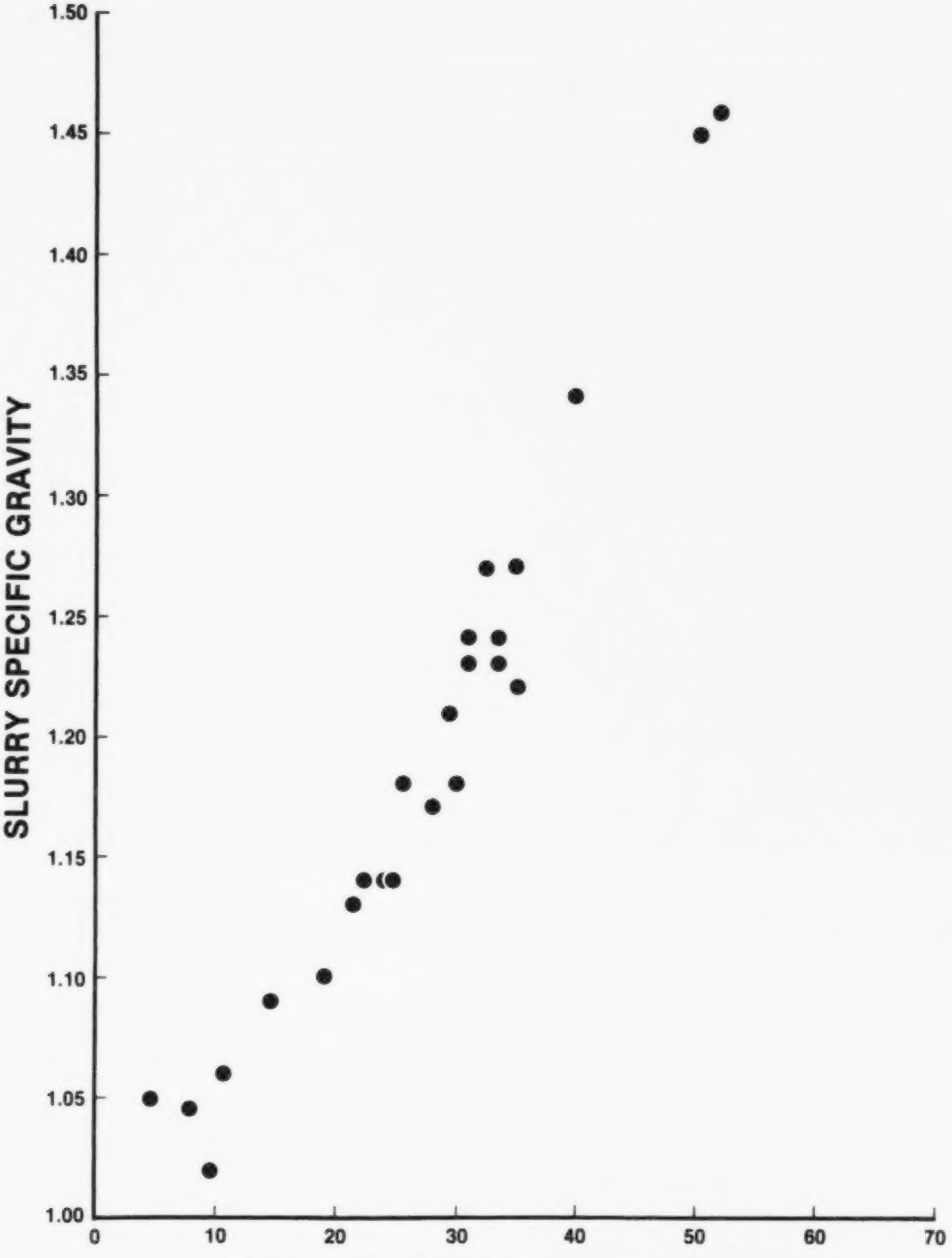

Figure B-4. Recycle Solids Slurry Specific Gravity Dependence on Solids Content.

The synthetic solution was formulated to represent a mixture of 25 percent clarifier underflow plus 75 percent cooling tower blowdown from the Comanche Station power plant. This mixture is typical of what might be available for dilution water in a commercial utility situation. Use of the mixture for slurry makeup and dilution during the demonstration run had no deleterious effects on the performance of the dry scrubbing system.

PRODUCT SOLIDS

Comparisons of the particle size distributions of spray dryer and fabric filter product solids collected from various runs in the test program are presented in Appendix Figures B-5 to B-10. Samples were submitted for particle size data for a number of representative pilot test runs operating with and without recycle. The chemical compositions for the product solids from test runs are reported in Table 9.2.

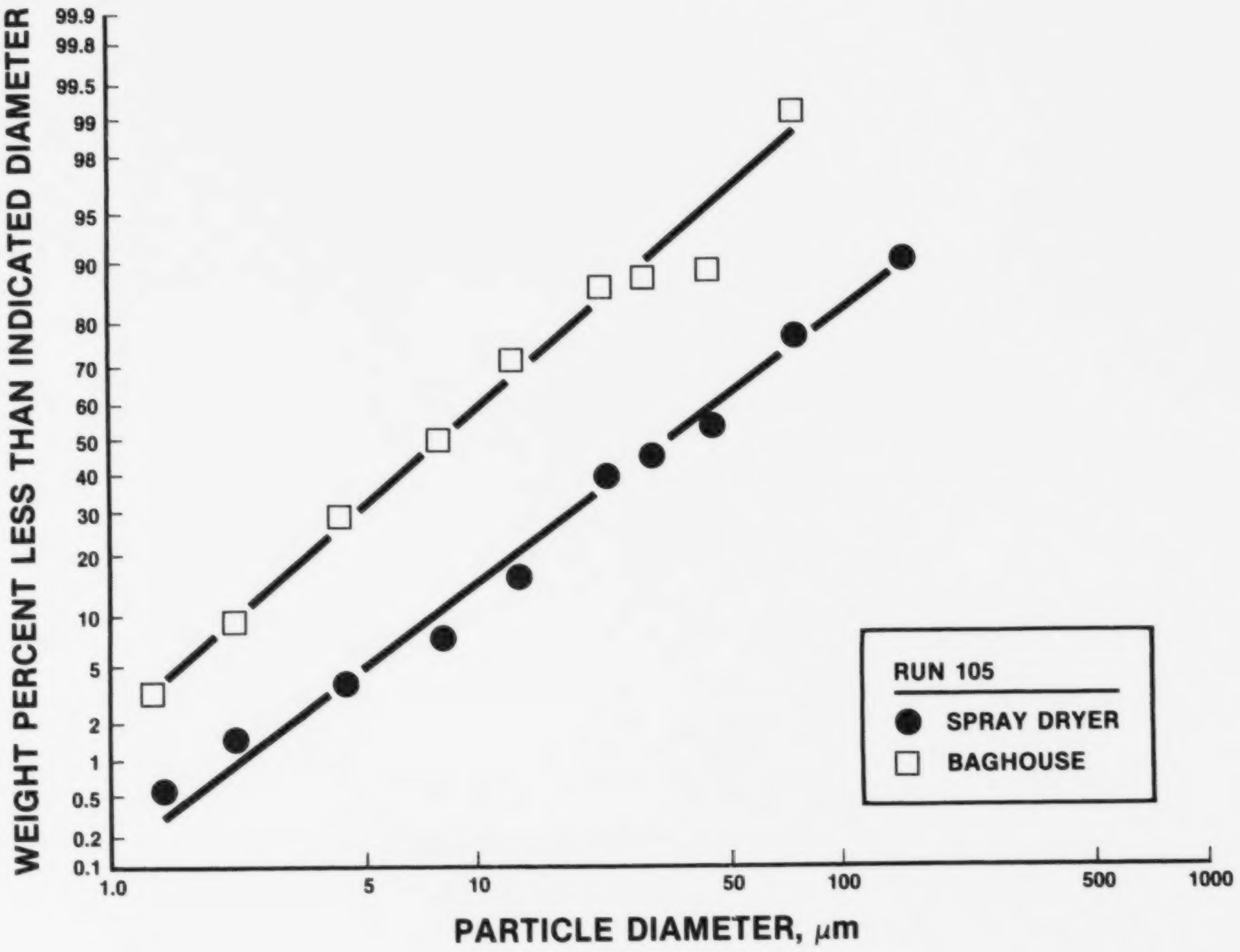

Figure B-5. Comparison of Spray Dryer and Fabric Filter Particle Size Distributions - Run 105.

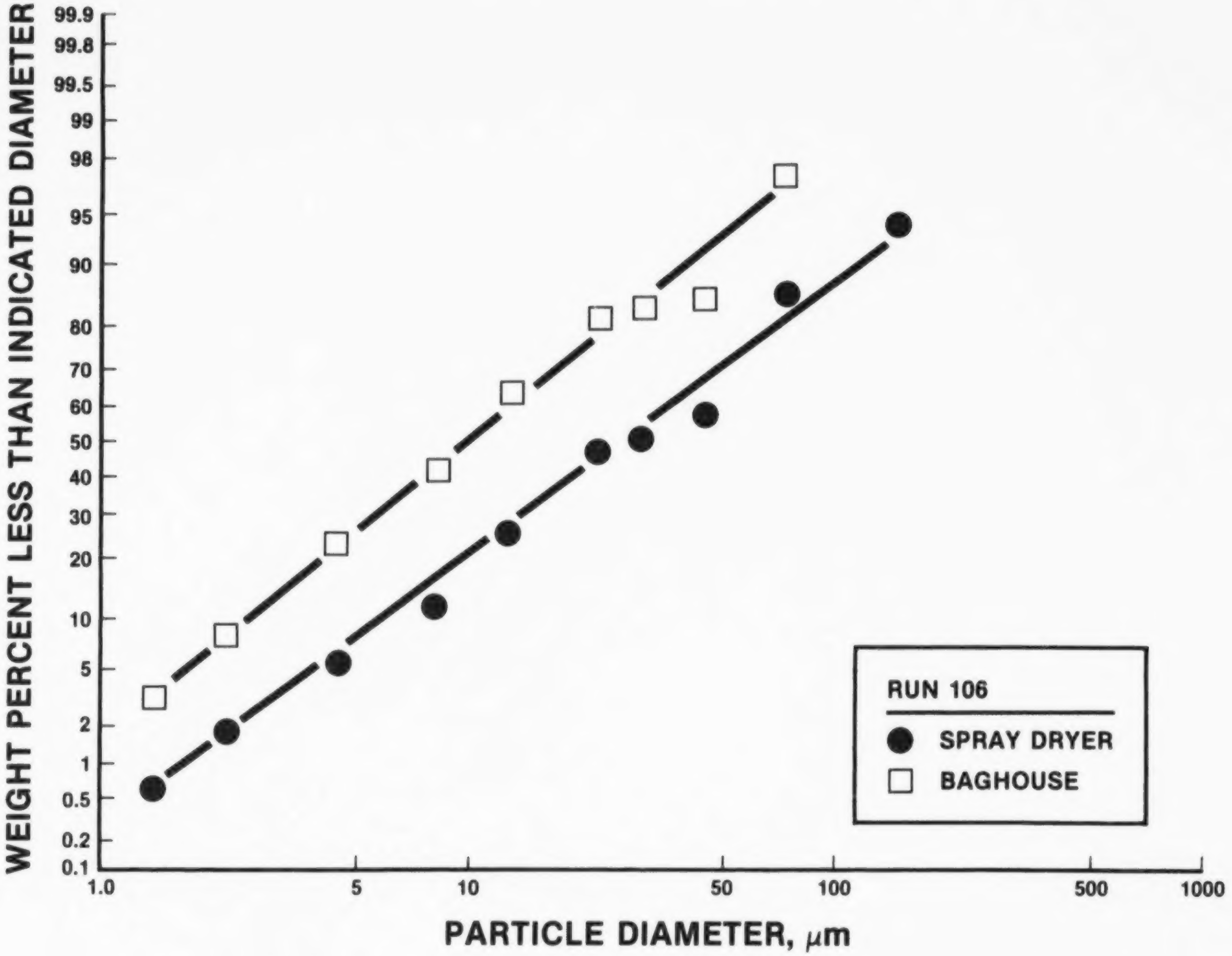

Figure B-6. Comparison of Spray Dryer and Fabric Filter Particle Size Distributions - Run 106.

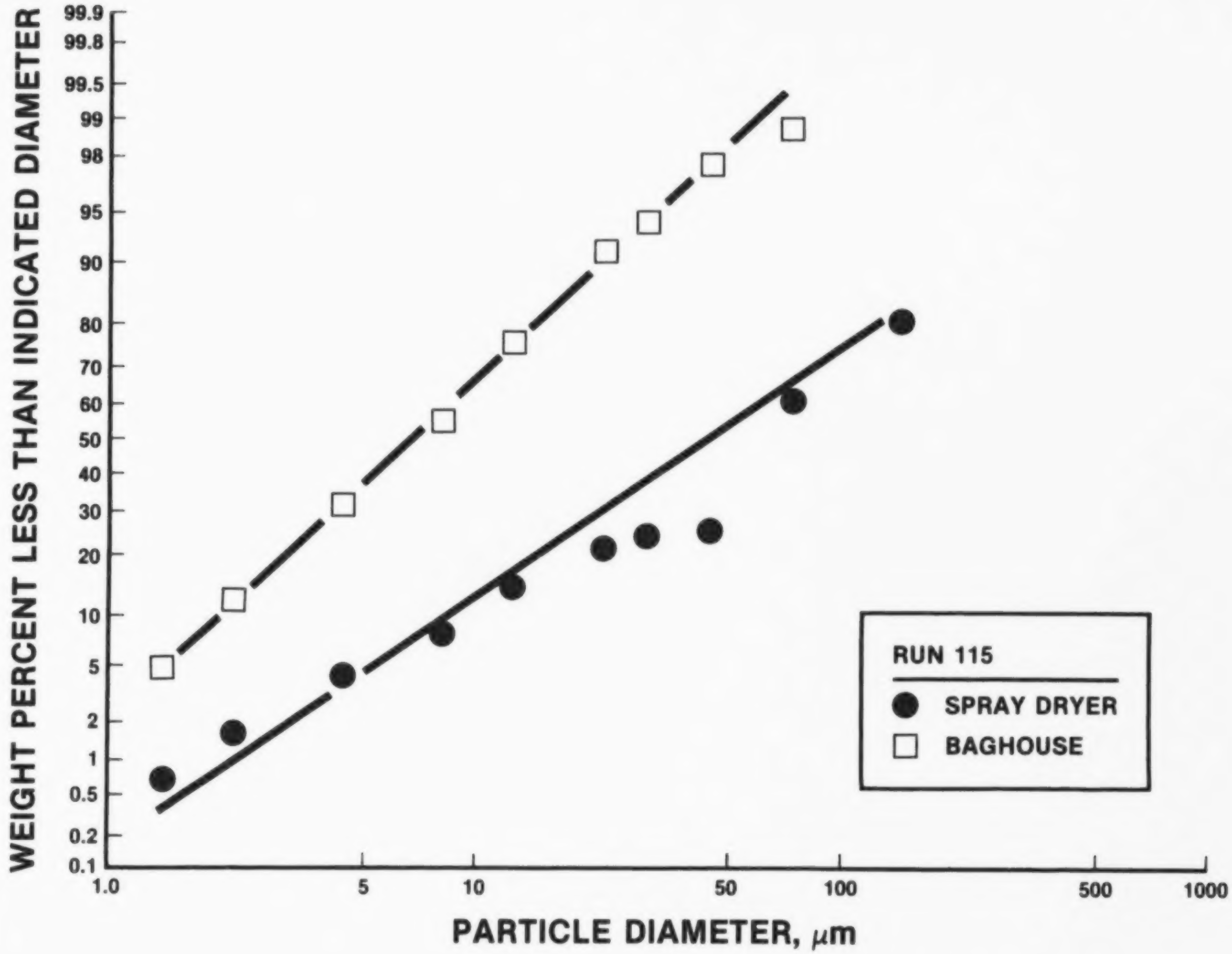

Figure B-7. Comparison of Spray Dryer and Fabric Filter Particle Size Distributions - Run 115.

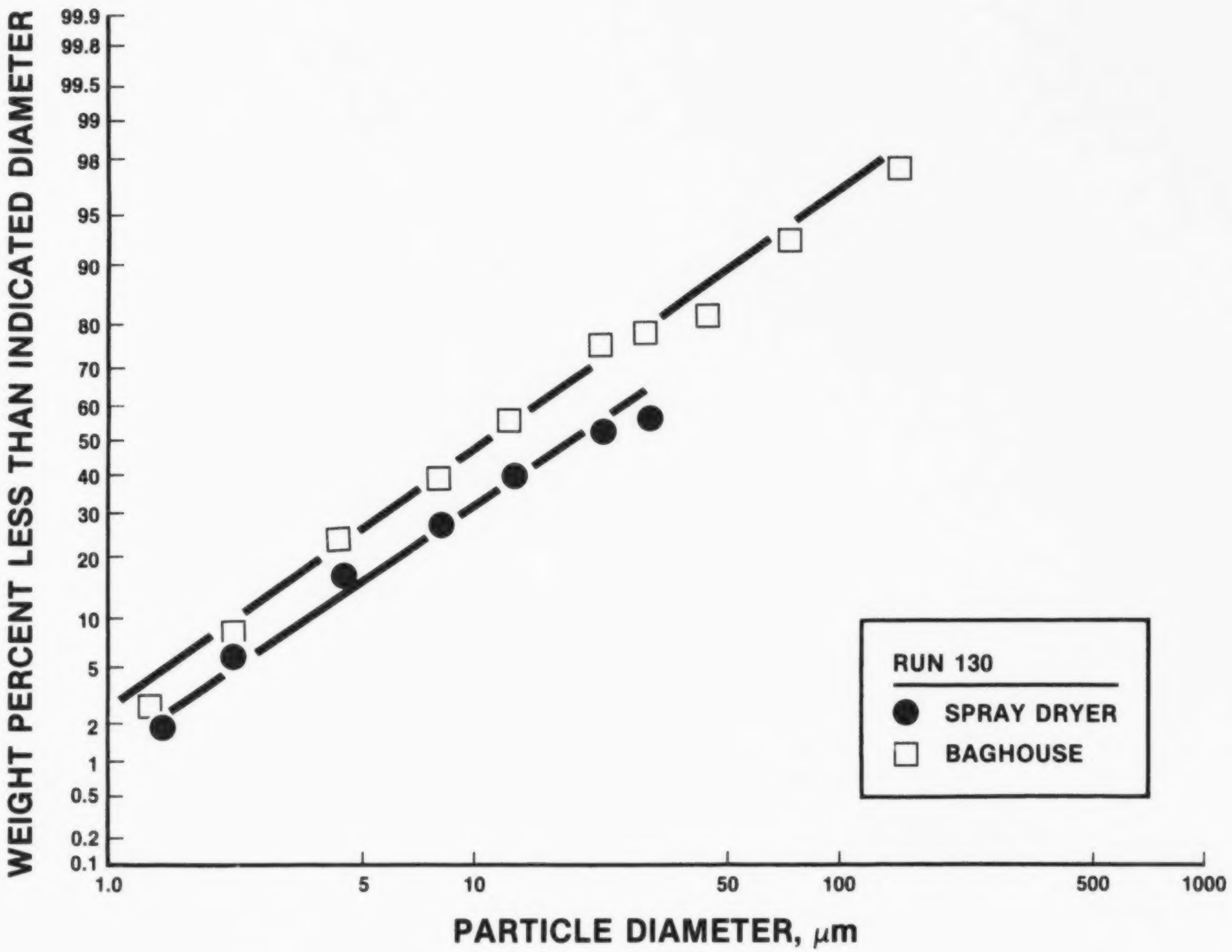

Figure B-8. Comparison of Spray Dryer and Fabric Filter Particle Size Distributions - Run 130.

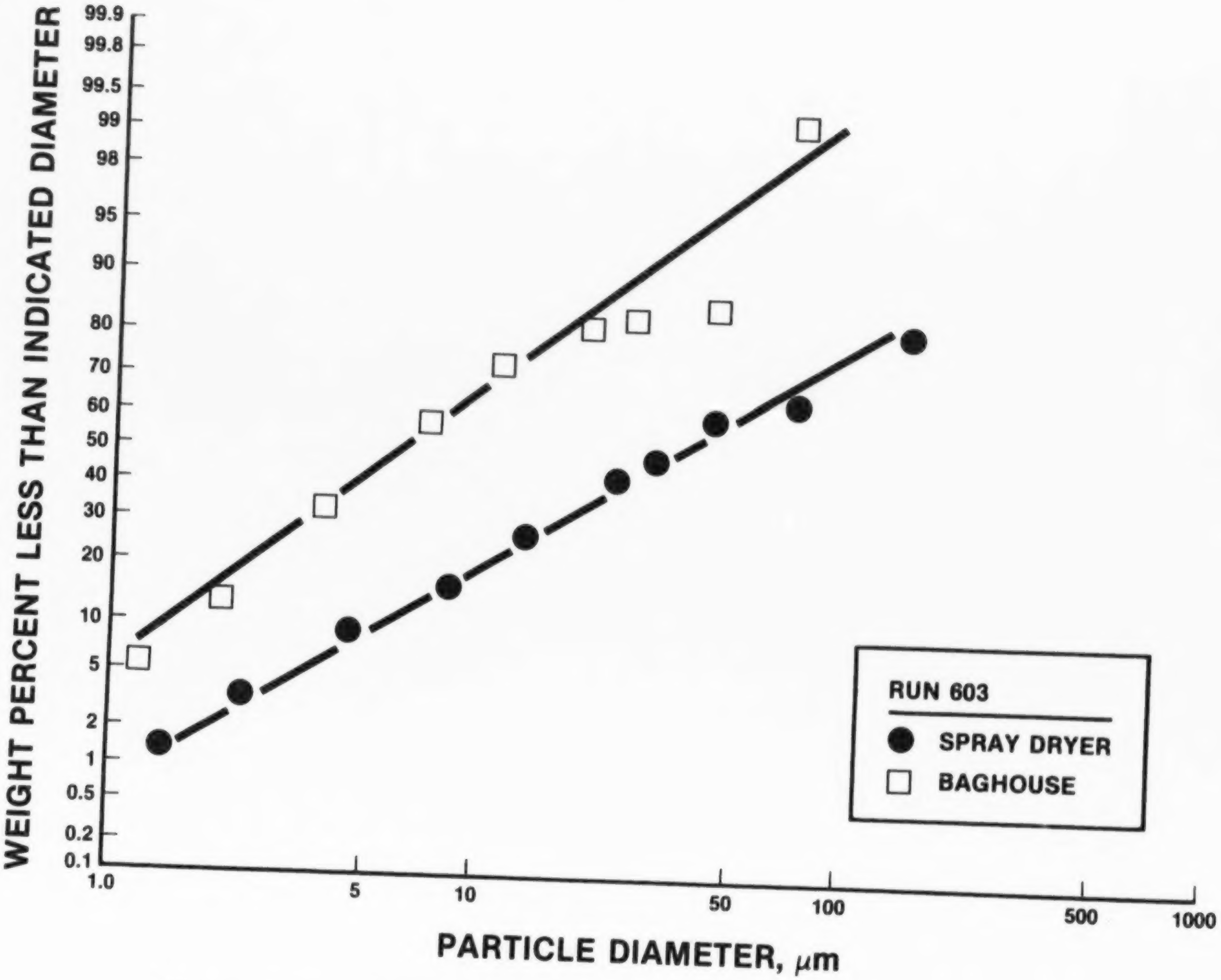

Figure B-9. Comparison of Spray Dryer and Fabric Filter Particle Size Distributions - Run 603.

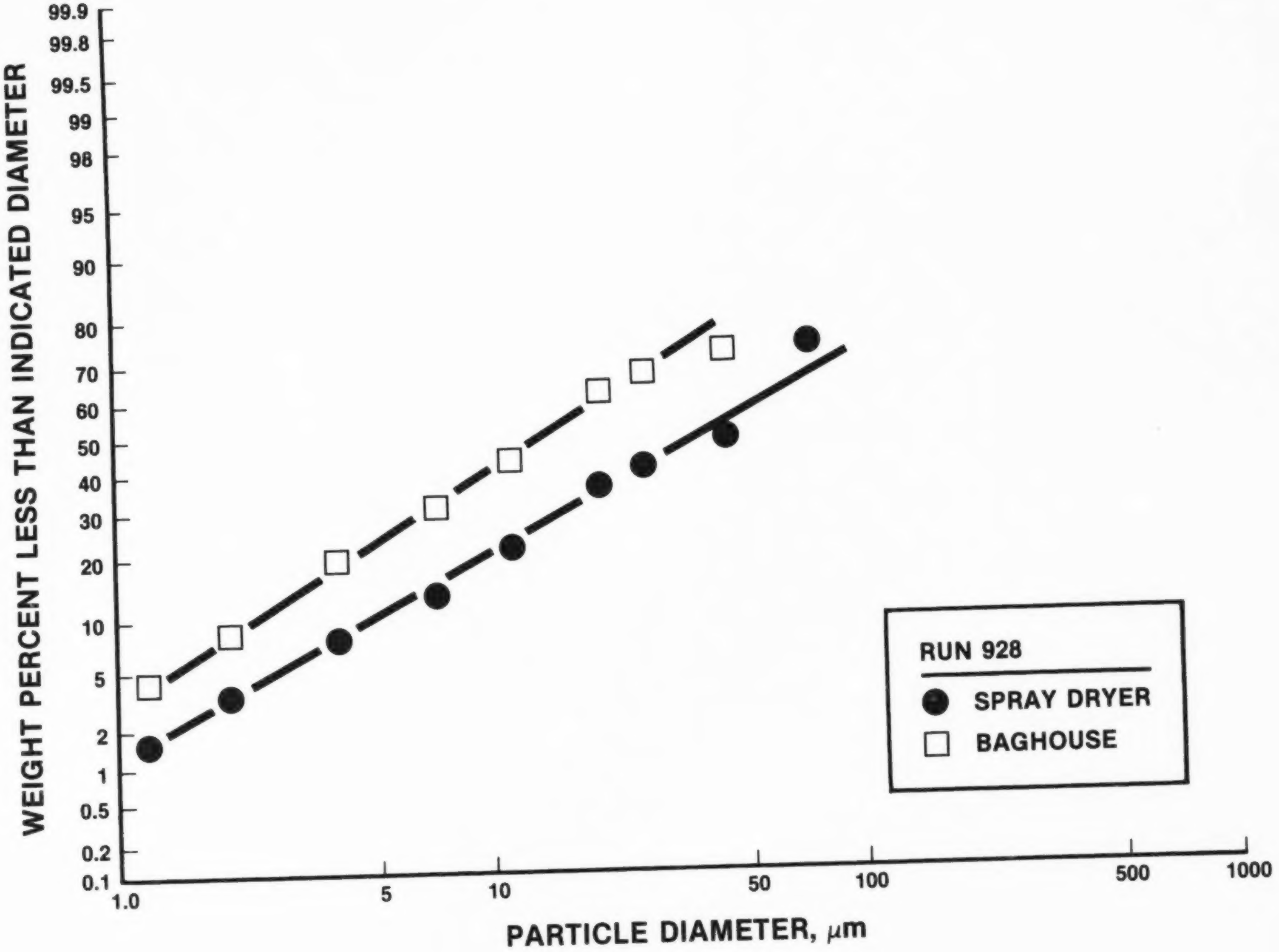

Figure B-10. Comparison of Spray Dryer and Fabric Filter Particle Size Distributions - Run 928.

APPENDIX C

ANALYTICAL METHODS

PRODUCT SOLIDS MAJOR COMPONENT ANALYSES

The dry SO_2 wastes contain the following components:

- Calcium Sulfite
- Calcium Sulfate
- Calcium Carbonate
- Calcium Hydroxide
- Moisture
- Flyash

Sulfites

Sulfites are analyzed by the regular iodometric procedure. Special precautions are taken for interference due to atmospheric oxygen (addition of dry ice to exclude air) and that due to iron (by adding NaF or phosphoric acid). $CaSO_3 \cdot \frac{1}{2}H_2O$ is determined from thermogravimetric analysis (TGA) and checked against the value obtained by iodometric titration.

Sulfates

Sulfates are analyzed, after removal of sulfite, as $BaSO_4$ gravimetrically or turbidimetrically depending upon their concentrations.

Carbonate and Hydroxide

When feasible carbonate and hydroxide contents of solids are determined by acid-base titrations (at pH 7 and 4 respectively). $CaCO_3$ is determined by thermogravimetric analysis. $Ca(OH)_2$ is determined by acid-base titration and confirmed by TGA analysis. In favorable cases, TGA provides the $Ca(OH)_2$ concentration directly.

Moisture

Moisture is determined either by TGA or gravimetrically by weight loss at 100 to 110°C.

Fly Ash Content

Research-Cottrell has developed a procedure to determine the amount of fly ash in the FGD solids/fly ash mixture. In this procedure, the SiO_2 content of the FGD/fly ash mixture is used as a marker to determine the total fly ash content of the sample.

The analytical procedures for thermogravimetric analysis (TGA), sulfate (gravimetric), sulfite, and chloride determination are presented below. A general procedure for preparing leachate solutions is also included.

QUALITY CONTROL AND ASSURANCE

The standard solutions used in the determinations are checked daily. A suitable standard (NBS or similar) is always run to check the accuracy of the analyses performed for each group of samples analyzed for a particular component. For each analysis, duplicate runs are made and the average of the two is taken, provided these two values fall within the acceptable range of the particular analytical method.

Dry SO_2 Scrubbing Waste Solids Thermogravimetric Analysis

The analyses performed on lime-based scrubber solids from the dry SO_2 scrubbing pilot plant utilize the technique of thermogravimetric analysis (TGA) developed by CES for previous FGD studies. Periodic wet chemistry tests are employed to spot check. The TGA technique involves heating a prepared sample of solid phase material at a specific rate over a predetermined temperature range and observing the weight change which results from solid state reactions occurring at different characteristic temperatures.

Solids sample preparation for analysis includes drying at 35°C for 24 hours, breaking up of the dried solids, and riffling as many times as needed to obtain a representative sample of about 2.5 gm. The prepared solid phase sample is then subjected to analysis on the thermobalance over a preprogrammed temperature range (ambient to 980°C) at a specific heating rate (80°C per minute). The resulting thermogram (plot of weight versus temperature) will exhibit, in a general case, associated weight losses of 2 moles of waters of hydration from $CaSO_4 \cdot 2\,H_2O$(130° to 200°C), 1/2 mole of water of hydration from $CaSO_3 \cdot 1/2\,H_2O$(400 to 425°C), 1 mole of water from dehydration of $Ca(OH)_2$ (575 to 625°C), loss on ignition from combustibles (700 to 750°C), and finally evolution of 1 mole of CO_2 gas from $CaCO_3$ (800 to 900°C). Measuring these losses and back calculating each for the particular constituent produces accurate analysis of the solids in only a few minutes of what normally would require hours or days for determinations by alternate means.

In addition to the various calcium compounds analyzed by TGA, it is possible to determine the concentration of $MgCO_3$ present. To separate the weight losses of CO_2 from $MgCO_3$ and the weight loss from the ignition of combustibles which overlap at 650°C, it is necessary to reanalyze the samples in a nitrogen environment where combustion does not take place. The observed weight loss under nitrogen is readily converted to equivalent $MgCO_3$.

To insure the data obtained from TGA analysis produces a high degree of accuracy, an alternate wet chemical method is employed periodically as a check. This wet test procedure uses the same sample employed in the TGA. The sample is digested in concentrated HCl, CO_2 and SO_2 are evolved and forced through an absorption train. The first gas washing bottle is filled with 3 percent hydrogen peroxide solution, which traps any SO_2 and forms H_2SO_4. The CO_2 gas also passes through the peroxide trap into a series of acid and moisture traps to a pre-weighed Miller bulb containing 20-mesh Ascarite, which absorbs the CO_2.

After the digestion has been completed, the reaction flask solution is tested for insolubles, calcium content by EDTA titration (also magnesium content if applicable), and total sulfate by gravimetric means. The solution in the peroxide trap is titrated for SO_2 using a $BaCl_2$ titrant and Thorin as an indicator. The Miller bulb is weighed to determine the amount of CO_2 absorbed. From data obtained from these tests, complete check analysis of all the consituents previously mentioned can be performed. Data obtained by this procedure matched TGA results quite closely in all samples tested.

Sulfate Determination

Procedure--

1. Accurately weigh a 1 to 2 g sample of solids and transfer to a beaker.
2. Digest the solids sample with 5 to 10 ml of 6N HCl. Filter the solution through a filter paper (Whatman No. 42). Dilute the filtrate with deionized water up to 250 ml in an Ehrlenmeyer flask.
3. Take a 25 ml aliquot from the Ehrlenmeyer flask filtrate and transfer it into a 250-ml beaker.
4. Add an equal amount of 4.0 M EDTA if the sample is highly colored (indicating the presence of iron).
5. Place a pH probe into the solution and adjust the pH of the solution with dilute NaOH to pH 2.0 to 2.5.
6. Add 50 ml of saturated $BaCl_2$ solution (100 g/l) to the pH-adjusted solution. A white precipitate will form if sulfate is present.
7. Place the beaker on a hot plate or in an oven at 70° to $80^\circ C$ for 1 hour. Stir the solution occasionally with a Teflon stirring rod.
8. Filter the solution through a pre-weighed Gooch crucible. Make sure the wall of the beaker has been cleaned using a rubber policeman and deionized water.
9. Dry the Gooch crucible at $110^\circ C$ for 2 hours and cool in a dessicator. Reweigh the Gooch crucible.

Calculation--

$$\text{Wt.\% Sulfate} = \frac{(\text{Dilution Factor})\ (\text{Wt. of } BaSO_4 \text{ ppt,g.})(0.4115)(100)}{\text{Sample Wt. (g)}} \qquad \text{(C-1)}$$

Sulfite by Iodometric Titration Analysis

Theory--
Upon addition of a known amount of acidified sample containing sulfite to an excess of iodine solution, the sulfite present reduces the iodine. The excess iodine remaining is determined with sodium thiosulfate using starch as indicator.

Reagents--

Starch Indicator--To 5 g starch in a mortar, add a little cold deionized water and grind to a paste. Pour into 1 liter of boiling deionized water ($\sim 100^\circ C$), stir and allow to settle overnight. If the starch paste does not go completely into solution, separate and collect the clear supernatant liquid. Preserve the clear liquid with 2 ml of chloroform.

Standard Potassium Iodate Solution--Accurately weigh about 35.7 g KIO_3 (primary standard grade, dried at $120^\circ C$ for 2 hours). Transfer to a 1 liter volumetric flask, dissolve with deionized water, and dilute to mark.

$$\text{Normality} = \frac{\text{wt. of } KIO_3\text{, g}}{35.667} \qquad \text{(C-2)}$$

Standard Sodium Thiosulfate Solution--Weigh 25 g $Na_2S_2O_3 \cdot 5H_2O$. Transfer to a 1 liter volumetric flask and dilute to mark with deionized water. Standardize as follows:

1. Dissolve about 2 g KI in 50 ml deionized water in an Erlenmeyer flask.

2. Transfer 5 ml of standard KIO_3 solution into the flask using a pipet.

3. Add 5 ml of 1:9 HCl.

4. Titrate with $Na_2S_2O_3$.

$$Na_2S_2O_3 \text{ Normality} = \frac{5 \text{ ml } KIO_3 \times N\ KIO_3}{\text{ml } Na_2S_2O_3} \qquad \text{(C-3)}$$

Standardize daily.

Standard Iodine Solution--Dissolve 76 g KI in about 500 ml deionized water. Add 25.4 g I_2. Stir until dissolved and dilute to 2 liters. Standardize daily against standard $Na_2S_2O_3$ solution.

Procedure--
1. Transfer 25 ml of standard iodine solution into an Erlenmeyer flask using a pipet. (More I_2 may be required if $SO_3^=$ is high.)

2. Accurately weigh an 0.1 g sample to be analyzed for sulfite content using an analytical balance. Transfer to a flask with deionized water. Stir to dissolve.

3. Add 5 ml of 1:1 HCl and immediately titrate with standard sodium thiosulfate solution to pale straw yellow.

4. Add a few ml starch indicator and titrate to deep blue end-point.

Calculations--

$$\text{ml } I_2 \text{ reacted} = \frac{\text{ml } Na_2S_2O_3 \times N\ Na_2S_2O_3}{N\ I_2} \qquad \text{(C-4)}$$

$$\text{Wt.\% } SO_3^{=} = \frac{\text{Total ml } I_2 - \text{ml } I_2 \text{ reacted}}{\text{Sample Weight}} \times 4 \times N\ I_2 \qquad \text{(C-5)}$$

$$\text{Wt.\% } CaSO_3 \cdot \tfrac{1}{2}H_2O = \text{Wt.\% } SO_3 \times 1.6125 \qquad \text{(C-6)}$$

Chloride Determination

Principle--

In a neutral or slightly alkaline solution, potassium chromate indicates the end-point of the silver nitrate titration of chloride. Silver chloride is quantitatively precipitated before red silver chromate is formed.

Interference--

Substances in amounts found in process waters normally analyzed will not interfere. Bromide, iodide, and cyanide register as equivalent chloride concentrations. Sulfide, thiosulfate, and sulfite ions interfere. However, sulfite is removed by treatment with hydrogen peroxide in a neutral solution, while sulfide and thiosulfate are removed by treatment with hydrogen peroxide in an alkaline solution. Orthophosphate, in excess of 25 mg/1, interferes by precipitation as silver phosphate. Iron, in excess of 10 mg/1, interferes by masking the end-point.

Reagents--

Chloride-Free Water--If necessary, use redistilled or deionized distilled water.

Potassium Chromate Indicator--Dissolve 50 g K_2CrO_4 in a little distilled water. Add silver nitrate solution until a definite red precipitate is formed. Allow to stand 12 hours, filter, and dilute the filtrate to 1 liter with distilled water.

Standard Silver Nitrate (0.0141 N)--Dissolve 2.395 g $AgNO_3$ in distilled water and dilute to 1000 ml. Standardize against 0.0141 N NaCl by means of the procedure described below. Standard silver nitrate solution, exactly 0.0141 N, is equivalent to 500 mg Cl per 1.00 ml.

Standard Sodium Chloride (0.0141 N)--Dissolve 824.1 mg NaCl (dried at 140°C) in chloride-free water and dilute to 1000 ml. 1.00 ml solution equals 500 µg Cl.

Special Reagents for Removal of Interference--

Aluminum Hydroxide Suspension--Dissolve 125 g aluminum potassium sulfate or aluminum ammonium sulfate, $AlK(SO_4)_2 \cdot 12H_2O$ or $AlNH_4(SO_4)_2 \cdot 12H_2O$, in 1 liter of distilled water. Warm to 60°C and add 55 ml concentrated NH_4OH slowly with stirring. After allowing it to stand about 1 hour, transfer the mixture to a large bottle. Wash the precipitate by successive additions, with thorough mixing, and decantations of distilled water until free from chloride. When freshly prepared, the suspension occupies a volume of approximately 1 liter.

Phenolphthalein Indicator Solution.

Sodium Hydroxide, 1 N

Sulfuric Acid, 1 N

Hydrogen Peroxide, 30%

Procedure--

Use a 100 ml sample or a suitable aliquot diluted to 100 ml. If the sample is highly colored, add 3 ml $Al(OH)_3$ suspension. Mix, allow to settle, filter, wash, and combine filtrate and washings.

If sulfide, sulfite, or thiosulfate is present, make the water alkaline to phenophthalein with sodium hydroxide solution. Add 1 ml H_2O_2 and stir. Neutralize with sulfuric acid.

Titration--

Titrate samples in the pH range 7 to 10 directly. Adjust samples not in this range with sulfuric acid or sodium hydroxide solution. Add 1.0 ml K_2CrO_4 indicator solution. Titrate with standard silver nitrate to a pinkish yellow end-point. The means of consistent end-point detection are left to the individual analyst. Standardize the silver nitrate titrant and establish the reagent blank value by the titration method outlined above. A blank of 0.2 to 0.3 ml is usual for this method.

Calculation--

$$\text{mg/l Cl}^- = \frac{(A - B) \times N \times 35,450}{\text{ml sample}} \qquad \text{(C-7)}$$

where: A = ml titration for sample.
B = ml titration for blank.
N = Normality of $AgNO_3$.
mg/l NaCl = mg/l Cl^- x 1.65

General Procedure for Preparing Leachate Solutions

1. Collect the portion of solids sample that passes through a 60 mesh Tyler screen. Sample may require grinding. Weigh out a convenient amount of sample (10 to 20 g) into a tared dish, dry at 103°C for 1 hour, seal, cool, and reweigh to determine the amount of moisture in the sample.

2. Place the dried sample into a flask, add distilled water (500 to 1000 ml), and place on a magnetic stirrer for 2 hours (or some other period that may be specified by the person who submitted the sample).

3. Filter the sample, then dry and weigh the residue to determine the percentage of insoluble material.

4. Retain the leachate (filtrate) in a capped bottle and make the determination for all parameters using this solution.

5. Calculate all results on a dry basis.

6. Record all steps, times, weights, etc. throughout the entire process.

APPENDIX D

GLOSSARY

1. Spray Dryer Approach to Adiabatic Saturation, $\Delta T_{AS/SD}$, is defined as the spray dryer flue gas outlet temperature ($T_{OUT/SD}$) minus the spray dryer flue gas adiabatic saturation temperature ($T_{AS/SD}$):

$$\Delta T_{AS/SD} = (T_{OUT/SD} - T_{AS/SD})$$

2. Spray Dryer Temperature Drop, ΔT_{SD}, is defined as the spray dryer inlet flue gas temperature ($T_{IN/SD}$) minus the spray dryer outlet flue gas temperature ($T_{OUT/SD}$):

$$\Delta T_{SD} = (T_{IN/SD} - T_{OUT/SD})$$

3. Spray Dryer Residence (Retention) Time, Θ_{SD}, is defined as the total spray dryer volume divided by the volumetric flow rate of flue gas exiting the spray dryer:

$$\Theta_{SD} = \frac{\text{Total Spray Dryer Volume (ft}^3\text{)}}{\text{Gas Flow Rate out of Spray Dryer (acfs)}}$$

4. Fabric Filter Approach to Adiabatic Saturation, $\Delta T_{AS/FF}$, is defined as the fabric filter outlet temperature ($T_{OUT/FF}$) minus the fabric filter flue gas adiabatic saturation temperature ($T_{AS/FF}$):

$$\Delta T_{AS/FF} = (T_{OUT/FF} - T_{AS/FF})$$

5. Fabric Filter Air-to-Cloth Ratio, A/C, is defined as the actual gas flow entering fabric filter divided by the total bag surface area:

$$A/C = \frac{\text{Actual Gas Flow into Fabric Filter (cfm)}}{\text{Total Bag Surface Area (ft}^2\text{)}}$$

6. Recycle Solids Ratio, RR, is defined as the pounds of recycle solids per pound of fresh (makeup) calcium hydroxide fed to spray dryer:

$$RR = \frac{\text{lb Recycle Solids}}{\text{lb Fresh Ca(OH)}_2}$$

7. Spray Dryer SO_2 Removal, ε_{SD},%, is defined as the weight rate (lb/hr) of SO_2 removed within spray dryer divided by the flow rate (lb/hr) of SO_2 entering the spray dryer multiplied by 100:

$$\varepsilon_{SD},\% = \frac{(\text{lb/hr } SO_2 \text{ into S.D.}) - (\text{lb/hr } SO_2 \text{ out of S.D.})}{(\text{lb/hr } SO_2 \text{ into S.D.})} \times 100$$

8. Fabric Filter SO_2 Removal, ε_{FF},%, is defined as the weight rate (lb/hr) of SO_2 removed within fabric filter divided by the flow rate (lb/hr) of SO_2 entering the fabric filter multiplied by 100:

$$\varepsilon_{FF},\% = \frac{(\text{lb/hr } SO_2 \text{ into F.F.}) - (\text{lb/hr } SO_2 \text{ out of F.F.})}{(\text{lb/hr } SO_2 \text{ into F.F.})} \times 100$$

9. Overall SO_2 Removal, ε_{OV},%, is defined as the weight rate (lb/hr) of SO_2 removed within spray dryer/fabric filter system divided by the flow rate (lb/hr) of SO_2 entering the system multiplied by 100:

$$\varepsilon_{OV},\% = \frac{(\text{lb/hr } SO_2 \text{ into System}) - (\text{lb/hr } SO_2 \text{ out of System})}{(\text{lb/hr } SO_2 \text{ into System})} \times 100$$

10. Stoichiometric Ratio, SR, is defined as the actual moles of fresh (makeup) calcium hydroxide introduced into the system divided by the moles of calcium hydroxide theoretically required for complete reaction with all of the SO_2 entering the system:

$$SR = \frac{\text{Actual moles/hr Fresh } Ca(OH)_2 \text{ Entering System}}{\text{Theoretical moles/hr } Ca(OH)_2 \text{ Entering System}}$$

11. $Ca(OH)_2$ Utilization, (% Lime Utilization), is defined as the percent overall SO_2 removal divided by the stoichiometric ratio:

$$\% \text{ Lime Utilization} = \frac{\% \text{ Overall } SO_2 \text{ Removal}}{SR}$$

APPENDIX E

CONVERSION FACTORS

To Convert From English	To SI	Multiply By
scfm ($60^\circ F$)	nm^3/hr ($0^\circ C$)	1.61
cfm	m^3/hr	1.70
ft	m	0.305
ft^2	m^2	0.093
ft^3	m^3	0.028
gr/scf	kg/m^3	0.00229
in.	m	0.0254
in. H_2O	Pa	249
lb	kg	0.454
gal	m^3	3.79
gal/1000 ft^3	liters/m^3	0.13
BTU	joule	0.252
short ton	tonne	0.91
ft/sec	m/s	0.305

The temperature conversion formula between English and SI units is:

$$\frac{^\circ F - 32}{9} = \frac{^\circ C}{5} \qquad \text{(E-1)}$$

where: $^\circ F$ = degrees Fahrenheit
$^\circ C$ = degrees Celsius